Studies in Environmental Economics:

Numerical Analysis of Greenhouse Gas Policies

Charlotte Nilsson

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Contents

Introduction and Summary

1. Introduction

This thesis consists of four essays within the field of environmental economics. Different types of Computable General Equilibrium models (CGE models) have been used to assess the economic consequences of greenhouse gas policies. The focus is mainly on the Swedish economy, but the EU economies and the global economies are also analyzed in one essay each. In short, three different models, with different geographical coverage, are used to analyze the following issues:

I. Swedish environmental and energy policy in an EU perspective. What are the consequences of acting alone as opposed to engaging in multilateral agreements? What are the effects on emissions (carbon leakage), welfare, and trade?

II. Is trade with carbon permits always beneficial? If we consider secondary benefits from reducing CO_2 emissions, i.e. the reduction of other environmentally harmful gases resulting from energy use and the combustion of fossil fuel, what is the total cost of buying permits abroad as opposed to a reduction of CO_2 at the national level?

III. Burden sharing in international agreements is the fruit of negotiations and is full of compromises for all parties. Are these negotiation targets equitable, and can they be efficiently achieved? What are the economic consequences of different equitable permit distribution rules?

IV. Demand for transport services is the largest source of emissions of CO_2 from Swedish households. What are the effects of a carbon tax on household demand for different transport modes? Are different types of households differently affected, due to differences in consumption patterns? What kind of model extension is necessary to more accurately describe the household choice of transport services?

Environmental policy and CGE modeling

Computable general equilibrium models have been used for policy analysis since Johansen's (1960) multi sector growth model of the Norwegian economy. Numerical tax policy analysis was introduced shortly thereafter by Harberger (1962). Along with the development of algorithms and computers, CGE models have become increasingly popular for analyzing macroeconomic policy questions. Tax models have been used to analyze the excess burdens of current and proposed tax systems, and multi-country trade models have contributed to the understanding of effects of trade policies. Surveys of these types of CGE models are carried out in, for example, Shoven and Whalley (1984) and Bergman (1990). The increasing awareness of environmental problems along with the acceptance of economic instruments as a tool for handling these problems have resulted in a large literature where the effectiveness and/or equity effects of these instruments are analyzed using CGE models.

There are several reasons why general equilibrium analysis is preferable to partial equilibrium analysis of environmental problems. First, many environmental problems today originate from the use of fossil fuels. Therefore, most environmental policies will involve economic instruments affecting the price of these fuels as well as other sources of energy. Given that energy is a ubiquitous input in production and consumption, any such policy is likely to affect most sectors in an economy. Partial energy market analyses are likely to miss several important secondary effects, given the difficulties to take inter-industry linkages into account. These effects do not only occur due to price changes in intermediate inputs, but also due to the long-run substitution possibilities of energy inputs and primary factors. Second, a general equilibrium framework makes it possible to evaluate the instrument for tackling the externalities within the framework of the overall tax policy. It takes into account the many interactions between these instruments, public finance and the rest of the economy. Third, if the economy is open, several trade effects which are difficult to capture in a partial equilibrium framework are likely to occur.

Furthermore, if computable (numerical) equilibrium models are used in the analysis, it is possible to use a high level of disaggregation when simulating the policy effects of realistically specified policy instruments, and take into account the effects on, for example, trade, government budget and equity, which would be more or less impossible in an analytical general equilibrium model.

Needless to say, a CGE model used for environmental policy analysis needs to be specified to fit the environmental problem at hand. A "generic" model designed to analyze tax or trade issues most likely needs to be extended for the study of environmental issues. Obviously, detailed pollution calculations are preferable. To facilitate these calculations, emission origin must be identified, along with the specific (energy) inputs in production and/or consumption connected with the emissions. These inputs are preferably modeled as separate commodities and therefore, a relatively detailed specification of the energy sector is necessary. Integrated energy activity models and CGE models could be used for this purpose, as well as "top-down" CGE models with nested functions for energy use.

In this thesis, I have used a global, a regional and a single-country model to assess the economic consequences of greenhouse gas policies. All these models are CGE models of top-down structure, with nested functions for energy use. Below follows a short description of each model and for which kind of economic analysis it may be used.

The single country model EMEC

The EMEC model[1] was developed by Göran Östblom and myself at the National Institute of Economic Research in Sweden during the late 1990's. The model is a static computable general equilibrium model for Sweden, for the analysis of the interaction between the economy and the environment. In this thesis, two versions of the model are used. The basic framework of the two versions is well in line with mainstream CGE-models in the literature. However, it differs in some respect by including a relatively more disaggregated energy input structure and therefore facilitate simulations where substitution possibilities among energy inputs are possible. In the model, five energy commodities are specified: electricity, coal, oil, gas and bio-fuels. There are three atmospheric emissions (CO_2, SO_2, NO_x) linked to the use of energy. These emissions emerge from mobile and stationary sources, but also from industry processes.

Another feature of the model is the well described energy and environmental tax system. Due to the disaggregation of energy commodities, energy and environmental taxes are well described. These taxes are not treated as ad valorem taxes as in most other Swedish CGE models (Bergman 1996; Harrison and

[1] A model description may be found in Östblom 1999

Kriström 1999 and Hill 2001), but follow the structure of the tax system, i.e. environmental taxes are taxes on emissions[2].

This specification makes the model well suited for the analysis of environmental and energy policies within Sweden. The "original" EMEC model is used in Essay II, and in Essay IV, the EMEC model is extended with a new consumption module with special attention to household transport demand. The new extended model facilitates detailed analysis of the change in household demand (in particular the demand for transport services) due to a change in carbon tax. In the extended model, we have subdivided the households into 9 groups depending on income and residential area which may be used to study the distributional effects of a carbon tax.

The regional model GEM-E3

The GEM-E3 model was developed within the JOULE project (JOS3-CT95-0008) and is an applied general equilibrium model describing the economy, the energy system and the environment in each European Union member state, and at the European Union level. I joined the program in its second phase (1996/1997) and incorporated Sweden and Finland into the model so that all 15 member states are included. The GEM-E3 was one of the first regional models for the EU countries with a well-described energy and environmental module. The model is used in Essay I of this thesis.

In the GEM-E3 model, national economies are linked by endogenous trade and each country has the same model structure, but parameters and variables are country specific. Compared to the EMEC model, this model does not have as detailed description of the tax system and some country-specific features, such as the use of bio-fuels, are not incorporated. However, an advantage of the model is that a large part of the Swedish trading partners are modeled, which makes it possible to study carbon leakage effects and how trade is affected by different greenhouse gas policies in general.

The Global model GTAP-EG

The GTAP-EG model is used in Essay III. The model is built by Rutherford and Paltsev (2000) and I have made some minor changes to include trade with carbon permits. The GTAP-EG model is a static general equilibrium model built around

[2] The emission taxes are indexed by the GDP deflator.

two databases, the Global Trade Analysis Project (GTAP) database and energy statistics from the International Energy Agency (IEA). The GTAP dataset (version 4) represents global production and trade for 45 regions, 50 commodities and 5 primary factors in 1995. The IEA data provide a description of global energy flows. Together with energy price and energy tax information, it is possible to construct a consistent benchmark dataset representing the benchmark equilibrium at the core GTAP-EG model.

The GTAP dataset has been used in numerous studies of trade related issues. The GTAP-EG data and model have also provided a useful laboratory for energy-environmental related policy assessments. Two characteristics of the dataset and the model make them particularly suitable for the analysis undertaken in Essay III. First, the dataset divides the European countries into several regions, of which Sweden is one. This is clearly important for a meaningful assessment of the effects on the Swedish economy of international greenhouse gas policy pursuits. Second, the data and the model are specifically tailored for the economic analysis of multi-regional greenhouse gas agreements. Carbon dioxide emission data and emission permits are included in the static model.

2. Summary of the essays

This thesis uses CGE models as a tool for providing new insight into the economics of the greenhouse gas (GHG) problem. The first three essays contribute by deepening the understanding of the economic effects of GHG policies and pointing out new aspects of the problem that are important when evaluating policies. The fourth essay contributes to CGE-modelling by extending the model in a way that is important for GHG policy analysis. In other words, the results presented in this thesis are relevant primarily to Swedish policy, but they can also contribute to a deeper understanding of the effects of environmental policy reforms in general. Below follow a short summary of each essay in this thesis.

2.1 Essay I: A Unilateral versus a Multilateral Carbon Dioxide Tax: A Numerical Analysis with the European Model GEM-E3

The costs and effects of a unilateral Swedish decision to reduce carbon dioxide emissions are analyzed in this essay. The results of a unilateral reduction are compared to the results of an implementation of a European Union multilateral agreement. The question of how a country is affected by a unilateral versus a multilateral agreement is not new, but despite the importance of the global carbon dioxide issue, there has so far been no tool for numerically estimating the effects on the Swedish economy in a multi-country environment. The European model GEM-E3 makes an analysis possible and the results are different from earlier Swedish studies where single country models are used (e.g. Harrison and Kriström 1996).

Using the quasi-dynamic multi-country model, GEM-E3, the following two main results are obtained. First, the unilateral increase in the carbon dioxide tax rate induces a carbon leakage effect. Despite a more than 15-percent decrease in Swedish carbon dioxide emissions, as compared to the reference scenario for the year 2020, the aggregate EU emissions increase slightly. Second, the environmental benefits are obviously higher in the multilateral case, but the Swedish welfare effects (not including environment), GDP and other macroeconomic variables decrease as compared to the unilateral scenario. This may seem counter-intuitive for a small country like Sweden, but the imposed carbon dioxide tax increases the price level in all European countries and decreases the demand for goods in the EU. The change in terms of trade puts pressure on the current account and as a consequence the interest rate must increase to secure the balance in the current account. The negative income effect that affects the EU countries when implementing a common carbon dioxide tax is due to the relative price change, as compared to the rest of the world. In all simulations, the rest of the world produces goods at the same price as in the reference case, which implies that the EU loses shares on the world export markets, due to increased export prices. If the rest of the world were also implementing a carbon dioxide tax, a different result might be expected.

2.2 Essay II: Is CO_2 Trading Always Beneficial? A CGE-Model Analysis on Secondary Environmental Benefits.

International emission trading is a textbook example of an efficient way of reducing global pollutants, such as CO_2 emissions. However, some writers emphasize cases when CO_2 trading as such does not necessarily guarantee an efficient emission reduction. In this paper, we have considered another critical argument, i.e. secondary benefits. If there are other important environmental goals than only reducing CO_2 emissions related to energy use and the combustion of fossil fuels, the reduction of carbon content in the atmosphere has positive side-effects that should be taken into account.

In a CGE-modeling framework, we have analyzed the Swedish environmental goals conforming to the Kyoto Protocol, when simultaneously meeting national goals to alleviate acidification and eutrofication effects by reducing SO_2 and NO_x pollutants. We have found that when secondary benefits of measures aiming at reducing CO_2 are taken into account, it may still be in the government's interest to nationally decrease CO_2, instead of engaging in seemingly low-cost trading.

Our simulations have been based on the actual Swedish tax structure, including carbon dioxide tax. Therefore, we have also investigated how a switch to an abatement policy of "importing" CO_2 reductions affects private and government consumption. We could not find any negative effect, simply because CO_2 taxes today still constitute such a small share of the total tax base and the government budget.

2.3 Essay III: Equity in International Agreements on Greenhouse Gases.

Allocating the burden between parties is at the focus of interest in the international negotiation process on climate protection. The principles for allocation are many, and in this essay, I focus on principles based on economic welfare theory. This approach makes the allocation equitable and consistent with economic theory. I also include an analysis of some more ad hoc rules such as "ability to pay", "sovereignty", "egalitarian principles" and distribution per land area. My main conclusion from these simulation exercises is that the distribution rule based on the different assumptions on the social welfare function and some other more ad hoc distribution rules offers quite large changes in welfare, distributions of emission rights and contrary to earlier literature, I find that the initial distribution not only gives second-order effects but affects equilibrium prices and therefore, income.

At first, the simulations are restricted to the case where the Kyoto protocol's total emission target for the Annex 1[3] countries is assumed to hold and no permit trading is allowed between regions. Scenarios built on the utilitarian welfare function and the more ad hoc distribution rule "ability to pay" require large amounts of abatements for the Eastern European countries and the Former Soviet Union. Another observation from these simulations is that among the distribution rules tested, that based on maximizing the Bernoulli-Nash social welfare function is closest to the burden sharing agreement within the Kyoto protocol. The Bernoulli-Nash social welfare function strives at reducing the welfare differences between regions.

If the focus is turned to Sweden, I observe that the new discussions at the political level to reduce emissions even further than the -4% target are not in line with any of the distribution rules tried in this study, except the case where emissions targets are based on the relative emissions of the base year.

The second step involves the introduction of international carbon permit trade. These simulations show that permit trade is not unaffected by an initial distribution of carbon permits. The distribution of permits does not only have distributional effects between countries but also real effects on the world economy. This result contradicts earlier literature in the field (e.g. Oliveira Martins and Strum 1998), where the income effect is neglected.

The third step includes the introduction of a damage function and a cooperative solution is found, i.e. the social optimal total emission reduction and the distribution of permits. Also in these scenarios, different social welfare functions are assumed to include equity and value judgments in the optimal solution. Contrary to Tol (2001) the results indicate that the higher distaste for inequality the less stringent is the optimal CO_2 reduction target for the cooperative countries. Naturally, there are difficulties in comparing the two types of model results emerging from Tol's analysis with an integrated assessment model and the results from the general equilibrium model used in this study. An integrated assessment model has several feedback effects from the environment to the economy, while the economy is more endogenous and better described in a general equilibrium model

[3] Annex 1 = OECD member states (not including Korea, Mexico and Turkey), Bulgaria, Estonia, Latvia, Liechtenstein, Monaco, Romania, Russian Federation and Slovakia.

(as in this study). In a relatively "short" perspective, the feedback effects from the environment to the economy of increased CO_2 emissions will be less important while the economic reactions to the CO_2 constraint are more pronounced.

2.4 Essay IV: Household Transport Demand in a CGE-framework.

An increasing demand for models that can be used for analyzing the economic consequences of different environmental and energy policies has induced a growing demand for models more accurately describing the behavior of each agent regarding its energy use. In most studies, the main focus has been on either model improvement regarding energy production or stationary energy demand within the industry (i.e. Böhringer 1998). In this essay, however, I focus on transport issues and, in particular, how households' demand for transport services can be improved in CGE models. There are a few others modelers who have improved their CGE models regarding household demand for transport services (Van Dender 2001; Mayeres 2000 and Munk 2003); however, they mainly focus on congestion and accordingly, extensions important for that question. They also use stylized data. In this essay, I take a broader approach and start off by examining the variables of importance for household behavior reported in the literature of transport economics. Then, I use real data and incorporate as many variables as possible in the improved model. The new features of the consumption module are applied to a static general equilibrium model called EMEC. The results of the extended model indicate that by taking most of the variables shown to be of importance in the econometric transport literature into consideration, the effect of a carbon target will give somewhat different results, as compared to the non-extended model. A differentiation between trip purposes and trip length, a complementary relationship between work journeys and labor supply, and a subdivision of households by density of population and income, influence the numerical results in a direction increasing the negative welfare effect of a carbon target, as compared to the non-extended model.

The complementary relationship assumed to exist between work trips and labor supply counteracts the decrease in transport demand, due to an increasing CO_2 tax. This is why the CO_2 tax rate is higher in the extended as compared to the non-extended model and subsequently, the welfare effects become higher in the extended model. At the micro level, the transport mode choices also differ between the extended and the non-extended model. In the extended model, a substitution away from private transports (car use) to public transports (road, train and air) takes place, whereas a general substitution away from both public and private transports is visible in the non-extended model. This micro result is due to the division into trip purpose and the general nesting structure, so that transport demand cannot be directly substituted for any other commodity.

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I

A Unilateral versus a Multilateral Carbon Dioxide Tax

A Numerical Analysis with the European Model GEM-E3[*]

Charlotte Nilsson[†]

Abstract

This paper analyzes and compares the effects of a common reduction of CO_2 emissions within the European Union to a Swedish unilateral decision to reduce CO_2 emissions. For this purpose, a numerical general equilibrium model, GEM-E3, has been used as the analytical tool. The model covers all European Union countries, with production disaggregated into 18 sectors. The 13 consumption goods included are classified into three consumption categories (durable, non-linked non-durable and linked durable goods) to improve the energy allocation description. In addition, the industry exemption of CO_2 tax is studied.

The results indicate that if Sweden unilaterally decides to increase its carbon dioxide tax, the total European Union carbon dioxide emissions will increase, i.e. there will be a "carbon leakage effect". Perhaps more surprising, a European Union multilateral implementation of a carbon dioxide tax rate will induce lower welfare (excluding environmental benefits) in Sweden, as compared to the situation where the same carbon dioxide tax is unilaterally introduced.

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1. Introduction

During the last decades, there has been growing concern about the rise in the concentration of greenhouse gases in the atmosphere. These gases cause what is commonly known as the "greenhouse effect" or "global warming" and are one of the main environmental threats of today. Even small levels of global warming could disturb the adaptation of the ecosystem, resulting in the expansion of deserts, a more humid climate which will increase the spread of diseases, effects on farmlands especially in dry areas, etc.. Such changes would have a dramatic impact on economic life. Even though there is extensive uncertainty, not to say controversy, about the magnitude of the damage from global warming, many politicians and scientists argue that it is important to start reducing the emissions of greenhouse gases now, because of the inertia of the climate system and the long life cycle of the emission in the atmosphere[1].

Several international agreements have been signed, aiming at reducing the emissions of greenhouse gases. The most recent international agreement was signed in Kyoto (Japan) in December 1997, where the European Union (EU) was one of the signatories[2]. According to EU policy, each member state must achieve its EU-agreed country-specific goal, without resorting to a common EU policy. An alternative strategy would be to impose a common EU policy, e.g. an EU carbon dioxide tax which would, in a more direct way, secure the implementation.

If the common decision to reduce carbon dioxide emissions (one of the most important greenhouse gases) fall through, some countries might unilaterally decide to reduce their emissions. The arguments for such measures are that these countries hope to make at least some contribution, however small, in the right direction to reduce global CO_2 emissions, and that other countries may then be persuaded to follow suit. In this paper, the costs and effects of a unilateral Swedish decision to reduce carbon dioxide emissions are analyzed. The results of a unilateral reduction are compared to the results of the implementation of a European Union multilateral agreement. The question of how the Swedish economy would react to a common EU carbon policy has been discussed for several years in the Swedish greenhouse gas debate, but the possibility to analyze it in a multi country-model has not existed

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[1] See Grennfelt (1986) for a discussion about the biological characteristics of carbon dioxide.
[2] For details about the Kyoto Protocol, see "Kyoto Protocol to the United Nations Framework Convention on Climate Change".

until the GEM-E3[3] model was developed. The computable general equilibrium model, GEM-E3, is used as an analytic tool. In all scenarios, a carbon dioxide tax is used as the economic instrument to induce the reduction. In other words, the purpose of this paper is to compare the cost and effect of a Swedish unilateral and an EU multilateral decision to reduce CO_2 emissions.

1.1 Related literature

Nowadays, CGE models cover a large spectrum of environmental issues. These models mostly deal with man-made emissions of carbon dioxide, to a large extent arising from the combustion of fossil fuel. A few of these models focus on Sweden and the Swedish CO_2 reduction policy. Most of the Swedish models are single country models, which is a serious limitation: feedback effects from other countries are not reflected, nor are the imported effects of policies in other countries. This is an unrealistic feature for a small economy, especially if important trading partners are influenced by an economic shock.

The most recent study covering the issue of climate control policies in Sweden was carried out by the Green Tax Commission appointed by the Swedish Government. A single-country CGE model was used to study the effects of an increased carbon dioxide tax in Sweden (see Harrison and Kriström, 1996). Another Swedish single-country CGE model has been developed by Bergman (1991), who has studied the overall effects of Swedish environmental policy. The present paper relates the problems studied in Harrison and Kriström (1996) and Bergman (1991) to a European perspective. Moreover, by using the GEM-E3, the difference between a unilateral and an internationally coordinated policy can be analyzed.

There are other multi-country models, which are used to study the problem of global warming and the reduction of greenhouse gases[4]. The OECD Secretariat has developed a large multi-country CGE model, GREEN (Van der Mensbrugghe 1994), that can be used to quantify the economy-wide and global costs of policies to curb the emissions of carbon dioxide. The GREEN model is highly aggregated, both in sectors and countries. For example, the European Union is one aggregated country (region) so Sweden cannot be studied separately. In the GEM-E3 model,

[3] See European Commission (1995) for a background to the GEM-E3 project.
[4] See OECD (1993) for a survey of global models.

all EU countries are represented separately and can therefore be analyzed in more detail. Another multi-country model is presented in Böhringer et al. (1997). This model is designed for calculating the cost sharing schemes in connection with reduced CO_2 emissions. The model focuses on Europe, but it only covers six of the EU member states, Sweden not being one of these.

The rest of the paper is organized as follows. Section 2 gives a general description of the GEM-E3 model[5]. In Section 3, the underlying conditions of the simulations are discussed and Section 4 presents the scenarios and the scenario results. Section 5 concludes.

2. The GEM-E3 model

The GEM-E3 model is an applied general equilibrium model describing the economy, the energy system and the environment in each European Union member state[6], and at a European Union level. National economies are linked together by endogenous trade; each country has the same model structure, but parameters and variables are country specific.

There are eighteen producing sectors: four sectors (sectors 2-5 in the Appendix, table A1) for the supply and distribution of energy and the remaining sectors are broad aggregates of the rest of the economy[7]. The production in each sector is modeled as a nested constant elasticity of substitution (CES) production function (see the Appendix, figure A1). This implies that demand for inputs and primary factors in each sector follows a procedure involving several steps. In each step, inputs and primary factors are optimally combined according to a constant returns to scale CES production function and producer behavior is modeled on the standard assumption of profit maximization in a perfectly competitive environment.

The two primary factors of production are capital and labor. The labor market is assumed to be perfectly competitive, and total labor supply is determined by the utility maximization of households[8]. For each period, the model endogenously allocates the available labor force over sectors. Capital is a quasi-fixed variable,

[5] For a detailed description and a complete list of all model equations see Nilsson (1998), which is available from the author (charlotte.nilsson@konj.se)
[6] The model covers all European Union countries; Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden and the UK.
[7] See Appendix table A1 for a complete list of the production sectors.
[8] Unemployment is modeled as voluntary.

and is defined such that the firm can change next year's capital stock, by investing in the current year. Further, the stock of capital is assumed to be immobile between sectors and countries.

Government production is modeled in the same way as the other producing sectors in the economy. Thus, the use of inputs is determined through cost minimization and government expenditure, investment demand and tax levels will be treated as exogenous. Financing of government expenditures is provided by nine different sources of government revenues: indirect taxes, environmental taxes, direct taxes, value-added taxes, product and export subsidies, social security contributions, import duties, foreign transfers and profits or losses from state-owned firms.

The households are modeled as one representative household, which can supply labor, save, invest and consume thirteen consumer goods. The model distinguishes between three consumption categories: durable goods, linked non-durable goods and non-linked non-durable goods (see the Appendix, table A2). The categories are introduced to improve the model's ability to replicate the relationship between durable goods such as "Heating appliances" and "Transport equipment", and the energy (linked non-durable goods) these durable goods require, i.e. to improve the energy allocation description. It is particularly important to capture this relationship when the modeling implications of a CO_2 tax, since consumption of durable goods is affected by energy price changes.

The representative household allocates its resources in an inter- and intra-temporal environment. Its consumption behavior, derived from utility maximization, can be described in two steps (see the Appendix, figure A2). First, the household allocates its resources between future and present consumption, given the wage rate, the interest rate and the long-term social time preference. In the second step, the household takes total consumption in a period as given and makes an intratemporal decision about how to allocate it between the different consumer goods in the economy[9].

The demand for products by households, producers and the public sector constitutes total demand, which is allocated between domestic and imported products, following the Armington specification. In this specification, cost-minimizing sectors and households use a composite commodity combining domestically produced and imported goods, which are considered as imperfect

[9] See Figure 2, the household consumption scheme.

substitutes. The GEM-E3 model also distinguishes between goods imported from EU countries and the rest of the world. An index for the optimal allocation of imported goods according to country of origin and price is calculated, which is then used to allocate consumption between imported and domestically produced goods, as discussed above.

The rest of the world (non-EU countries) is largely treated as exogenous in the GEM-E3 model. The import demand for good i from the rest of the world depends on the ratio between the export price set by the exporting European country and that of the rest of the world. The export of good i from the rest of the world to the European Union is exogenous.

Countries are further assumed to apply a uniform rule for setting export prices, independent of the country of destination. The Armington assumption implies that the various countries within the European Union can supply exports at different prices. Finally, the total amount of exports is derived by the fact that the total volume of exports of good i from country u to country v should equal the total volume of imports of good i from country u to country v.

Emissions of several environmentally harmful gases are linked to the consumption of fossil fuels. The government has economic instruments at its disposal for controlling the consumption of the corresponding energy products. Here, a carbon dioxide tax is the only economic instrument. It is uniform across sectors and energy products, but the actual amount paid by each sector differs with energy product and sector, because of industry exemptions.

The absence of financial assets in the model implies that the absolute price level is exogenous. All prices are in relative terms and the exchange rate is the numeraire. The ratio between the current account and GDP is fixed for each European country, and the real interest rate is the variable that will adjust so that this relationship is fulfilled.

3. Scenario conditions

The model is calibrated to fit benchmark data for 1985. The GEM-E3 project began in 1994 and at that time, the only year for which Eurostat had a complete data set for the SAMs (Social Accounting Matrix) for all European countries was 1985. Böhringer et al. (1997) had the same base year problem. In their simulations, they use 1985 "as if" it were 1995. There was little change in the Swedish production structure between 1985 and 1995. The largest change is the expansion of the equipment goods industries (sectors 9-11). In 1985, these sectors constituted 13 percent of total production while in 1996, their share had grown to 17 percent. Also in this case do simulations use 1985 "as if" it were 1996.

The Swedish carbon dioxide tax structure from 1996 is the starting point of the simulations in this study. The manufacturing industry only pays 25 percent of the carbon dioxide tax rate, while the emission from purely industrial processes and electricity production are completely exempt. In scenarios where a carbon dioxide tax is implemented in all European countries, the Swedish structure is imposed on all countries. No consideration is given to the phase-out of nuclear plants in Sweden or any other European country. All countries have a fixed current account, and changes in CO_2 tax revenue is assumed to be redistributed to the household as a lump sum.

4. Scenario results

4.1 A scenario description

The purpose of the simulations in this paper is to analyze the long-term effects of carbon dioxide reducing policies within the European Union. The focus is on Sweden and the model is run through the year 2020, in 5-year steps. A carbon dioxide tax is the policy instrument used to enforce the reduction. The scenarios analyze the effects of a Swedish unilateral tax and a common European Union tax. Some attention will also be paid to the question of industry exemptions.

The results of the scenarios are presented with the focus on Sweden. The CO_2 tax used in all scenarios is twice the 1996 Swedish CO_2 tax (0.74 SEK/kg CO_2 emission). Table 1 presents the scenarios.

Table 1. A description of the scenarios

Reference Scenario	A business as usual scenario where there is no change in the economic structure as compared to the initial year.
Scenario 1	A Swedish unilateral carbon dioxide tax is introduced. For the remaining European countries, there are no changes as compared to the reference scenario. The Swedish manufacturing industries pay a reduced rate of only 25% of the carbon dioxide tax rate.
Scenario 2	Same as scenario 1, but no exemptions for the Swedish manufacturing industries.
Scenario 3	A common European Union carbon dioxide tax rate is introduced. The same tax level and the same assumption regarding the manufacturing industries as in scenario 1, but applied to all EU manufacturing industries.
Scenario 4	Same as scenario 3, but no reduction for manufacturing industries.

4.2 A unilateral CO_2 tax in Sweden

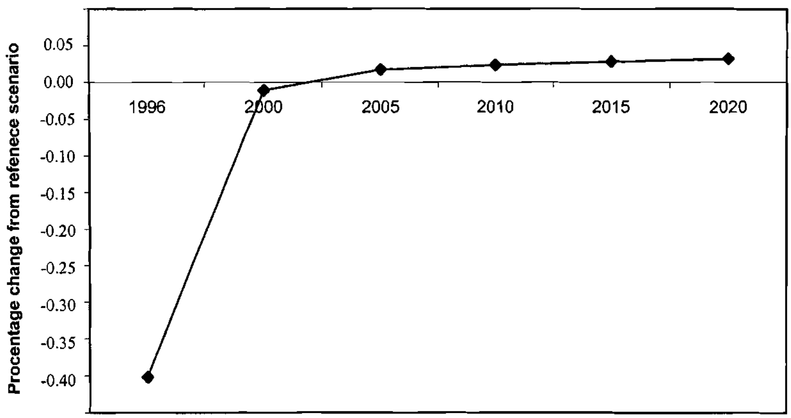
The results in table 2 show that introducing a unilateral CO_2 tax in Sweden has a very small effect (ceteris paribus) on the GDP of the aggregated European Union. Despite a more than fifteen percent change in Swedish carbon dioxide emissions, as compared to the reference scenario in 2020, aggregated EU emissions *increase*, for two important reasons. First, the Swedish share of CO_2 emissions is very small, not even three percent of total European Union emissions in the base year. A fifteen percent decrease only corresponds to a half percent decrease of total EU emission, ceteris paribus. Second, Sweden reduces its production and exports due to the relative price changes. Other countries, some of which are EU members, then take over the Swedish world market shares. When production moves, so does energy consumption and, accordingly, also emissions. This phenomenon is referred to as the "carbon leakage effect", i.e. production, and hence emissions, simply move to another country. The new producers consume more carbon intensive fuels or produce with a technology requiring more energy as compared to Swedish producers. Furthermore, the GDP of the European Union as a whole decreases slightly. In the no exemption scenario, these effects are intensified, but the total change of EU CO_2 emissions is negative due to the larger decrease in Swedish domestic demand, which outweighs the effect of the EU carbon leakage. However, excluding Swedish emissions, total EU carbon dioxide emissions will increase in both scenarios

Table 2. EU results, percentage change from reference scenario in the year 2020.

EU average	Scenario 1	Scenario 2	Scenario 3	Scenario 4
GDP	-0.08	-0.09	-2.0	-2.6
CO_2 emission	0.03	-0.14	-15.4	-20.4

The time profile for changes in CO_2 emissions within the EU are illustrated in Figure 1. The emissions of carbon dioxide decrease by almost the entire Swedish reduction during the first simulation year. Then, especially during the period 1996-2000, firms adjust to the new opportunities and start producing and emitting more. Shortly after the first five-year period, the EU emissions are above the reference level and slowly increase during the remaining periods.

Figure 1. Percentage change of carbon dioxide in EU in scenario 1, as compared to the reference scenario.



The effects on Sweden of the policy are shown in table 3. According to Scenario 1, both the capital stock and labor supply decrease during the simulation period, causing a reduction in GDP of 1.9 percent as compared to the reference scenario in 2020. Scenario 2 has similar trends in the macroeconomic variables, but these are more poignant. Private consumption, which hardly changes between the two scenarios, is an exception. The interest rate is higher in Scenario 2, implying a stronger negative effect on private consumption, but this effect is outweighed by the relative increase in real disposable income.

Table 3. Macro results for Sweden. Percentage changes from the reference scenario in the year 2020.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
GDP	-1.9	-2.5	-2.1	-2.5
Labor supply	-1.8	-2.2	-1.9	-2.0
Investment	-2.2	-2.9	-2.8	-3.3
Private consumption	-1.0	-1.1	-1.8	-1.9
Exports by volume	-5.5	-7.8	-6.5	-8.1
Imports by volume	-3.3	-4.4	-4.8	-6.0
Consumer price index	8.2	9.2	9.2	9.0
GDP deflator	2.8	3.0	2.7	2.2
Real wage rate	-3.8	-4.6	-4.8	-5.2
Real interest rate	1.3	1.5	1.6	1.8
CO_2 emissions	-15.7	-20.6	17.0	20.6
EV in millions of SEK	-11985.9	-16123.4	-16484.1	-18954.4
EV/CO_2 reduction*	-0.9	-0.9	-1.2	-1.1

*SEK per kilo of emission

The final macroeconomic results are obtained through a number of general equilibrium effects. The direct effect is an increase in fossil fuel consumer prices, propagated by the cost functions and the input-output structure. The process of transmission generates substitution and income effects for both producers and households. The CES production function allows the producer some leeway in changing the input structure, in case of a relative price change. Consequently, when prices of fossil fuels increase, a direct effect is a substitution away from fossil fuels cf. Figure A1 in the Appendix. Substitution between the different fuels also occurs since coal, oil and gas have different carbon intensities. However, a complete removal of fossil fuels is not possible, due to the finite elasticities in the production process. Households are affected by the price change in much the same way. The consumption of fossil fuel, and thereby the consumption of durable goods, decreases due to the substitution effect, cf. Figure A2 in Appendix.

The relative measure in SEK "Equivalent Variation per kilogram of carbon dioxide reduction" (EV/CO_2) is approximately equal in the two unilateral scenarios and indicates a welfare cost of 0.9 SEK per kilogram of carbon dioxide reduction (see table 3). This variable may be considered as the average cost of abatement for

Sweden, as opposed to the tax rate which represents the marginal cost of abatement. The indicator of welfare cost per unit of environmental benefit might not be optimal, since the increase in temperature is a global problem, and there is no environmental benefit as long as the global emissions of carbon dioxide have not been reduced. A better measure would be "Equivalent variation per unit of global carbon dioxide reduction", but as a second best alternative, the "Equivalent variation per unit of European Union emission reduction" could be used. Then, the welfare cost per environmental benefit is enormously high in the unilateral scenarios, since the reduction of carbon dioxide is approximately zero within the European Union.

The microeconomic effects are even larger than the macroeconomic effects discussed above, cf. table 4. There is an economic structural change. The manufacturing sectors have decreased more than the service sectors. Even when the manufacturing industries only pay 25 percent of the full rate, a noticeable change towards services is observed. Despite the inertia of the substitution mechanisms in the input structure, the service sectors manage to keep a modest decrease in production, as compared to the energy-intensive industries (Sectors 6-8). High labor intensity and low fossil fuel dependency constitute the key to the success of the service sectors. The energy-intensive sectors, on the other hand, are strongly influenced by the CO_2 tax. Even though these sectors are exempt in Scenario 1, the effects are large as compared to the service sectors. The decrease in production is due to a relatively high proportion of fossil fuels in a rigid input structure. The characteristics of the energy-intensive industries lead to a large decrease in demand for labor in these sectors, both in Scenario 1 and Scenario 2.

Table 4. Swedish Domestic Production. Percentage changes from reference scenario in the year 2020.

	Scenario 1 Domestic Production	Scenario 2 Domestic Production	Scenario 3 Domestic Production	Scenario 4 Domestic Production
Agriculture, forestry and fishing	-2.9	-3.6	-3.3	-3.7
Crude oil and oil products	-10.9	-13.6	-14.9	-17.5
Gas	-6.5	-15.1	-7.4	-15.1
Electricity	-6.6	-7.6	-7.3	-7.7
Ferrous and non-ferrous ore metals	-5.2	-10.4	-5.3	-8.5
Chemical products	-3.9	-7.7	-4.4	-7.5
Other energy intensive industry	-3.9	-6.3	-4.0	-5.8
Electrical goods	-3.6	-4.9	-4.2	-5.3
Transport equipment	-3.7	-4.9	-4.3	-5.1
Other equip. goods industry	-3.7	-5.2	-4.4	-5.7
Consumer goods industry	-2.4	-3.3	-2.8	-3.5
Building and construction	-2.2	-2.9	-2.8	-3.2
Telecommunication services	-1.5	-1.9	-2.1	-2.4
Transport	-6.5	-7.4	-6.9	-7.1
Credit and insurance	-1.7	-2.2	-2.0	-2.4
Other market services	-1.5	-1.8	-2.0	-2.2
Non-market services	0.0	-0.1	-0.1	-0.1

Table 5. Swedish exports. Percentage changes from reference scenario in the year 2020.

Sectors	Scenario1 Exports	Scenario2 Exports	Scenario3 Exports	Scenario4 Exports
Agriculture	-5.3	-5.5	-5.6	-5.8
Coal	-0.3	-0.1	-12.8	-18.9
Crude oil and oil products	-0.3	-0.1	-11.1	-12.8
Electricity	1.9	2.3	-0.1	-0.2
Ferrous and non-ferrous ore	-6.1	-12.7	-6.2	-10.2
Chemical products	-5.2	-10.6	-5.9	-10.8
Other energy intensive	-6.0	-10.3	-5.8	-8.5
Electrical goods	-4.1	-5.7	-5.2	-6.5
Transport equipment	-4.3	-5.8	-5.2	-6.2
Other equip. Goods ind.	-4.1	-5.7	-5.3	-6.8
Consumer goods industry	-6.1	-7.9	-6.8	-7.9
Telecommunication serv.	-5.3	-6.1	-5.8	-6.3
Transport	-15.5	-17.1	-15.9	-15.8
Other market services	-4.9	-5.3	-4.6	-5.0
Non market services	-3.4	-4.3	-3.3	-3.6

The increased price level of domestic production has a negative effect on exports, and the export decline is unevenly distributed across the sectors of the economy, cf. table 5. An important difference between the sectors is how other countries react to price changes in Swedish exports. The model assumes import demand from a specific country to be more sensitive to price changes in the manufacturing sectors, than in other sectors of the economy, which will add to the negative effects on the energy-intensive industries. Furthermore, these industries are very export oriented; they constitute more than 25 percent of total exports, but only 12 percent of total domestic production. Consequently, the large drop in energy-intensive exports will account for much of the decrease in total aggregated export.

The results in table 6 show that imports decline, despite an improvement in the terms of trade[10] (see table 7), since the import price decreases relative to the export price. The dominant effect on import demand is a decrease in total Swedish domestic demand. Moreover, the assumption that Swedes treat imports and domestically produced goods as imperfect substitutes is a crucial assumption for this result. The Armington elasticities prevent consumers from only consuming imported goods. As in the case of input goods in production, this will create an income effect, i.e. Swedes have fewer resources for buying imported goods, as compared to the reference scenario.

Table 6. Swedish imports. Percentage changes from reference scenario in the year 2020.

Sectors	Scenario1 Imports	Scenario2 Imports	Scenario3 Imports	Scenario4 Imports
Agriculture	-0.6	-1.2	-1.4	-1.9
Coal	-24.4	-37.6	-26.6	-38.1
Crude oil and oil products	-12.5	-16.1	-15.5	-18.3
Electricity	-6.8	-7.8	-7.5	-7.9
Ferrous and non-ferrous ore	-2.9	-4.9	-5.0	-8.3
Chemical products	-1.9	-3.2	-2.9	-4.7
Other energy intensive	-1.1	-1.8	-2.3	-3.5
Electrical goods	-2.1	-2.8	-3.0	-3.8
Transport equipment	-1.8	-2.4	-3.0	-3.7
Other equip. Goods ind.	-2.2	-3.1	-3.4	-4.3
Consumer goods industry	0.2	0.1	-0.9	-1.3
Telecommunication serv.	-0.4	-0.6	-1.1	-1.3
Transport	-0.4	-0.6	-4.2	-4.3
Other market services	-0.3	-0.5	-1.3	-1.4

[10] With the Armington assumption for foreign trade, part of the cost of carbon reduction may be passed on to the rest of the world through trade.

Table 7. Sector Terms of Trade[1] for Sweden. Percentage changes from reference scenario in the year 2020.

Sectors	Scenario 1 Terms of Trade	Scenario 2 Terms of Trade	Scenario 3 Terms of Trade	Scenario 4 Terms of Trade
Agriculture, forestry and fishing	3.7	3.9	3.0	2.9
Coal	-	-	-	-
Crude oil and oil products	-0.6	-0.8	-0.6	-0.7
Gas	0.3	-0.5	-0.9	-1.9
Electricity	-3.1	-3.8	-3.8	-4.0
Ferrous and non-ferrous ore metals	2.7	6.2	-0.1	-1.7
Chemical products	2.3	5.1	1.4	2.5
Other energy intensive industry	2.9	5.1	1.5	2.1
Electrical goods	1.8	2.7	1.4	1.8
Transport equipment	2.0	2.7	0.9	0.9
Other equip. goods industry	1.9	2.7	1.0	1.3
Consumer goods industry	2.5	3.3	1.6	1.9
Building and construction	4.6	5.3	5.1	5.1
Telecommunication services	3.5	4.3	3.0	3.5
Transport	7.9	8.9	1.8	2.2
Credit and insurance	2.7	2.6	2.4	1.7
Other market services	3.5	4.0	1.8	2.5
Non-market services	5.0	5.4	5.2	4.8

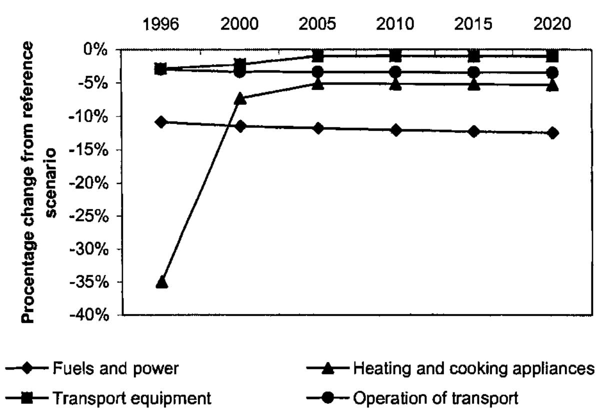
1) Terms of trade are here defined as the ratio between the export price and the import price.

The link between durable goods and linked non-durable goods in the household sector is obvious when looking at the consumption result in table 8 (cf. Figure A2 in the Appendix). All household goods increase slightly, except durable goods (heating appliances and transport equipment), linked non-durable goods (energy goods) and "Purchased transports". The price of "Purchased transports" and fossil fuels increase more as compared to other goods, which creates a substitution effect away from these goods. The durable goods "Heating appliances" and "Transport equipment" decrease due to the link with energy products (linked non-durable goods). At first, households react to the price changes by adjusting the stock of durable goods to fit the new market conditions. This is done by a substantial decrease in the consumption of new "Transport equipment" and "Heating appliances" cf. Figure 2. Once these adjustments have been made, the consumption paths are smooth, with only small changes. Energy consumption (linked non-durable goods), on the other hand, has no sudden movements and has downward sloping reduction curves during the entire simulation period.

Table 8. Household consumption in Sweden. Percentage changes from the reference scenario in the year 2020.

	Scenario1 Household consumption	Scenario2 Household consumption	Scenario3 Household consumption	Scenario4 Household consumption
Food, beverages and tobacco	0.4	0.4	-0.3	-0.6
Clothing and footwear	0.1	0.2	-0.3	-0.4
Housing and water	0.2	0.3	-0.6	-0.7
Fuels and power	-12.5	-13.5	-13.8	-13.9
Housing furniture	0.1	0.1	-0.2	-0.3
Heating and cooking appliances	-5.3	-5.8	-6.4	-6.6
Medical care and health expenses	0.0	0.0	-0.5	-0.7
Transport equipment	-1.0	-1.2	-1.6	-1.8
Operation of transport (petrol)	-3.5	-3.9	-4.1	-4.1
Purchased transport	-1.0	-1.1	-2.2	-2.3
Telecommunication	0.0	0.1	-0.7	-0.8
Recreation, entertainment and culture	0.2	0.3	-0.7	-0.9
Other services	0.0	0.2	-0.9	-1.1

Figure 2. Household consumption of durable and linked non-durable goods; results from scenario 1.



4.3 A common European Union CO_2 tax

The implementation of a common European Union CO_2 tax produces rather different economic reactions among the member states shown in table 9. In Belgium, GDP, labor supply and the carbon dioxide emissions have decreased more than in any other country. In contrast to the macroeconomic variables, Belgian households have managed to achieve only an *average* EU decrease in welfare. Belgium has the highest fossil fuel use per GDP among the member states. The manufacturing industries account for 45 percent of total Belgian production. Despite the exemptions of the manufacturing industries, the decrease in domestic production of manufactured goods is relatively large. Considering the significance of the manufacturing industries, it is not surprising that the whole Belgian economy is affected fairly hard, as a result of the higher price level. The increase in fossil fuel prices is transmitted through the input-output system and results in an overall higher price level. Domestic demand decreases because of the income effect, as do exports, labor supply and real wages. The pressure on the current account results in an increase in the interest rate, which will influence consumer behavior.

Contrary to what may be expected, Greece has the lowest carbon dioxide reduction and one of the lowest GDP and labor supply reductions. The result would be quite different if the fossil fuel input in electricity production were taxed. Greek power plants are highly fossil fuel dependent and in these scenarios, they are subsidized through the total exemption of carbon dioxide tax in this sector.

Table 9. Aggregated results, Scenario 3 percentage changes from reference scenario in the year 2020.

	GDP	Labor supply	CO_2 reduction	Equivalent variation as percentage of GDP[1]
Austria	-2.3	-1.6	-17.1	-0.7
Belgium	-3.1	-2.6	-22.3	-0.8
Germany	-2.2	-1.9	-14.0	-0.5
Denmark	-2.2	-1.7	-13.8	-0.3
Finland	-1.4	-1.0	-16.4	-0.5
France	-2.1	-1.7	-16.1	-0.4
Greece	-1.4	-1.6	-12.0	-1.7
Ireland	-2.7	-2.1	-20.1	-1.1
Italy	-1.6	-1.3	-15.1	-0.6
Netherlands	-1.6	-1.0	-13.2	-0.4
Portugal	-1.7	-1.0	-16.4	-0.7
Spain	-2.0	-1.7	-14.7	-0.7
Sweden	-2.1	-1.9	-17.0	-0.2
UK	-2.1	-1.0	-15.5	-0.9
EU average	-2.0	-1.5	-15.4	-0.6

1) (Final year EV / final year GDP -1)*100

The Swedish effects, as compared to the other European Union countries, are about average, but the equivalent variation expressed as a percentage of GDP is the lowest in the EU, due to the high electricity dependency of Swedish households.

Since electricity is not taxed in these simulations, this is a comparative advantage for Swedish households.

4.4 A Swedish unilateral tax versus a common EU tax

The carbon dioxide tax in Sweden is the same in the multilateral as in the unilateral scenario. Thus, the direct effects (increased fossil fuel prices) on Swedish sectors and households are the same in both scenarios. Despite this, the effects on the economy are higher in the multilateral than in the unilateral case, due to the income effect imposed on the economies because of the differences in terms of trade. In the multilateral scenarios, all European countries suffer from the direct effect of higher fossil fuel prices, and the price levels in all countries rise, due to the tax. The rise in the price level consequently increases the export prices for each European member state. Therefore, due to the trade specifications, import prices in Sweden will rise, as compared to the unilateral scenarios. Swedish import prices are determined according to the Armington assumption, which assumes imports to be imperfect substitutes for domestic production. In this model, they also differ according to country of origin. Thus, import prices are not world prices, but a mixture of prices from Swedish trading partners. If the relative import prices change, so does the mixture, but since the elasticities are finite, there will not be a complete switch to the cheapest trading partner. In other words, when the price level in the European countries increases, import prices in Sweden also increase, as compared to the case where only Sweden introduces a CO_2 tax.

The improvements in terms of trade have several positive effects on the Swedish economy. First, since the relative export prices have not decreased to the same extent as in the unilateral case, the negative effect on exports is weakened. This has a positive impact on domestic demand. Second, the improvement in terms of trade, as compared to the unilateral case, makes imports less advantageous. On the other hand, the decrease in EU demand decreases the demand for Swedish exports. Finally, the change in terms of trade also increases the pressure on the current account, thereby increasing the interest rate as compared to the unilateral case.

The energy goods lose market shares on the world market. The export products "Electrical goods", "Transport equipment" and "Other equipment goods" also decrease, which can, at least partly, be explained by the connection between consumer durable goods and linked non-durable goods. The increased price on fossil fuels in the EU reduces the demand for cars, since the price of petrol rises substantially. Another important factor negatively influencing "Other equipment goods" is the general decrease in investments throughout the EU. In the non-exemption multilateral scenario, exports of energy-intensive goods increase as compared to the unilateral case, i.e. Swedish production of these goods is relatively inexpensive.

A higher interest rate has a negative effect on private consumption, because it is preferable to save and invest in the future if the interest rate is high. Since utility depends on consumption and the value of voluntary leisure, the welfare indicator, Equivalent Variation, has decreased more in the multilateral than in the unilateral cases, mainly due to the higher wage and interest rate, and the fall in disposable income.

In contrast to the above mentioned variables, the reduction of Swedish CO_2 emissions is the same in Scenarios 2 and 4, due to the fact that the structural change in the economy is not as prominent in the multilateral case. However, Equivalent Variation per kilogram of Swedish CO_2 reduction is higher in the multilateral case than in the unilateral case, i.e. the welfare cost is higher per kilogram of Swedish carbon dioxide reduction. As previously discussed, it is not obvious that the Equivalent Variation per kilogram of Swedish CO_2 reduction is a good relative welfare measure. A better measure might be the Equivalent Variation per kilogram of global CO_2 emissions or the Equivalent Variation per kilogram of EU CO_2 emissions. If the latter measure were used, the welfare cost per benefit in the unilateral scenarios would be much higher than in the multilateral scenarios. When a common tax is introduced, all countries try to reduce their emissions and the carbon leakage effect ceases to exist, at least within the Union.

5. Discussion and conclusions

The question of how a country is affected by a unilateral versus a multilateral agreement is not new, but despite the importance of the global carbon dioxide issue, there has so far been no tool for numerically estimating the effects on the Swedish economy in a multi-country environment. The European model GEM-E3 makes an analysis possible and the results are different from earlier Swedish studies where single country models are used (e.g. Harrison and Kriström 1996). Naturally, this is not only due to the multi-country aspect of the GEM-E3 model, but also to the differences in production structure, dynamics, and base year, just to mention a few.

Using the quasi-dynamic multi-country model, GEM-E3, the following two main results are obtained. First, the unilateral increase in the carbon dioxide tax rate induces a carbon leakage effect. Despite a more than 15-percent decrease in Swedish carbon dioxide emissions, as compared to the reference scenario for the year 2020, the aggregate EU emissions increase slightly. Second, the environmental benefits are obviously higher in the multilateral case, but the Swedish welfare effects (not including environment), GDP and other macroeconomic variables decrease as compared to the unilateral scenario.

The carbon leakage effects indicate that pursuing commitments to decrease carbon dioxide emissions is not wise if the international agreement breaks down. However, one issue that has not been discussed in this paper is the fact that a decrease in carbon dioxide emissions also decreases other emissions causing local environmental damages, like sulphur dioxide and nitrogen oxides. These local environmental improvements might outweigh the global environmental drawback caused by carbon leakage.

When a multilateral action (scenarios 3 and 4) to reduce carbon dioxide emission is implemented, the negative effects on the Swedish economy are larger, both in welfare and GDP terms as compared to the unilateral case. This may seem counter-intuitive for such a small country, but the imposed carbon dioxide tax increases the price level in all European countries and decreases the demand for goods in the EU. The change in terms of trade puts pressure on the current account and consequently the interest rate increase to secure the balance in the current account. The negative income effect that affects the EU counties when implementing a common carbon dioxide tax is due to the relative price change as compared to the rest of the world.

In all simulations, the rest of the world produces goods at the same price as in the reference case, which implies that the EU loses shares on the world export markets due to increased export prices. If the rest of the world were also implementing a carbon dioxide tax, a different result might be expected.

The indicator "Equivalent variation per kilo of CO_2 reduction" is approximately equal in the two unilateral scenarios (exemption and non-exemption), but in the multilateral scenarios, this indicator is slightly lower in the non-exemption scenario. It is difficult to draw a precise conclusion from this, since the emission reductions are not equal in all scenarios. However, since it is more expensive to reduce emissions the larger the reduction and the non-exemption scenarios (scenarios 2 and 4) have higher absolute reduction as compared to the respective exemption scenarios (scenarios 1 and 3), the results obtained from the indicator are strengthened by this argument. Consequently, the scenarios indicate that industry exemptions do not lead to lower welfare costs per kilo of carbon dioxide reduction (environmental benefit) in the multilateral scenarios.

The link between durable goods and linked non-durable goods results in a change in consumption that cannot directly be connected to price changes in the economy. Households consume less "Heating appliances" and "Transport equipment", due to the increase in fossil fuel prices.

The model used in this study obviously lacks some important effects of tax reforms. One such effect is the substitution into alternative energy commodities, which could not be analyzed here since the GEM-E3 model does not allow for it. Preliminary results of a single country CGE-model (EMEC[11]) show that an increase of the carbon dioxide tax in Sweden substantially increases the use of biofuels, thereby decreasing the effects on the economy. Since the use of biofuels is a topical issue in the whole EU, this is an interesting area for more detailed further research.

[11] Environmental Medium term EConomic model (EMEC) is developed at the National Institute of Economic Research in Sweden.

Appendix

Table A1. Production sectors

1. Agriculture, fishery and forestry
2. Coal
3. Crude oil and oil products
4. Natural gas and other gas products
5. Electricity
6. Ferrous and non-ferrous ore and metal
7. Chemical products
8. Other energy-intensive industries
9. Electrical goods
10. Transport equipment
11. Other equipment goods industries
12. Consumer goods industries
13. Building and construction
14. Telecommunication services
15. Transports
16. Services of credit and insurance institutions
17. Other market services
18. Non-market services

Table A2. Consumer goods and their characteristics

Consumer goods:	Characteristics:
1. Food, beverages and tobacco	Non-durable good
2. Clothing and footwear	Non-durable good
3. Housing and water	Non-durable good
4. Fuels and power	Linked non-durable good
5. Housing furniture	Non-durable good
6. Heating and cooking appliances	Durable good
7. Medical care and health expenses	Non-durable good
8. Transport equipment	Durable good
9. Operation of transport	Linked non-durable good
10. Purchased transport	Non-durable good
11. Telecommunication	Non-durable good
12. Recreation, entertainment and culture	Non-durable good
13. Other services	Non-durable good

Figure A1. The Nested Production Function

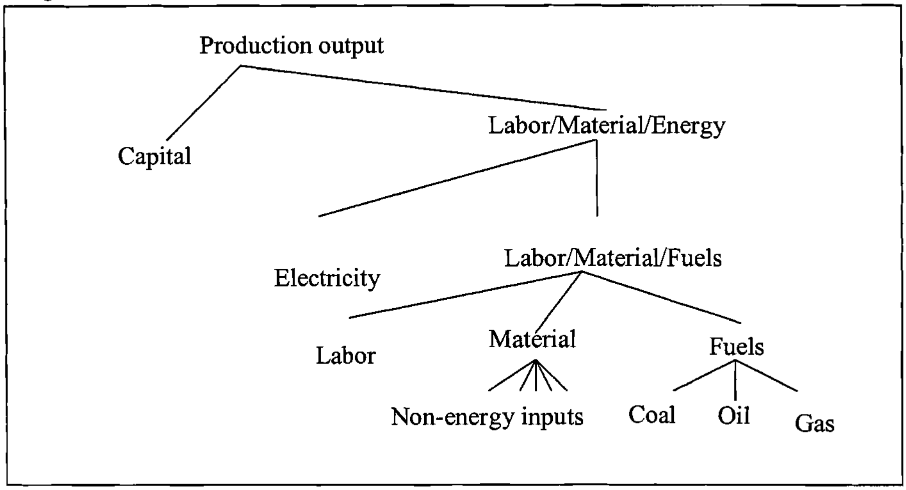
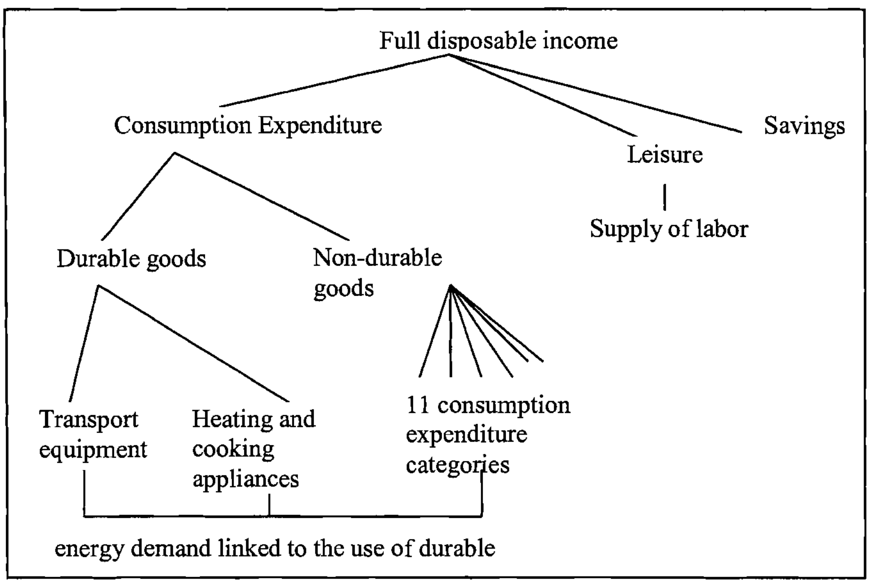


Figure A2. Household consumption scheme



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Is CO_2 Trading Always Beneficial?

A CGE-Model Analysis on Secondary Environmental Benefits*

II

Charlotte Nilsson† and Anni Huhtala‡

Abstract

This paper analyzes the cost-efficiency of trading CO_2 emissions by focusing on the overall environmental impacts of active climate policy measures. When reducing CO_2 emissions, other emissions, also related to the consumption of fossil fuels decrease at no additional cost. These secondary benefits must be taken into consideration when analyzing gains from international emissions trading. The Swedish environmental target to comply with the Kyoto Protocol by reducing greenhouse gases, and two national goals to alleviate acidification and eutrofication effects by reducing SO_2 and NO_x pollutants are simultaneously studied in a CGE-modeling framework. The results indicate that when secondary benefits are taken into account, it may still be in the government's interest to nationally decrease CO_2, instead of engaging in seemingly low-cost trading.

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1. Introduction

Several studies have shown that countries with high marginal costs for reducing their greenhouse gas emissions would benefit from international emissions trading. Trading would guarantee economic efficiency by minimizing the costs for achieving the national emission reduction targets agreed upon in Kyoto (Bohm, 1998; Matsuo, 1998; Mullins and Baron, 1997; Parry et al. 1998; UNCTAD, 1998).

However, there are factors that may reduce the expected total cost saving of trading CO_2 permits. The efficiency gains could be decreased because of the governments' potential to exercise market power (e.g. Burniaux, 1998). The possibility of high transaction costs may also decrease the efficiency gains (Liski, 1998). Furthermore, trade does not necessarily equally benefit all countries. As pointed out by Böhringer et al. (1998), the final outcome depends on the domestic substitution effect vs. the terms of trade effects. Permit buyers face lower marginal abatement costs after trade on the one hand, but their terms of trade worsen on the other hand. In addition, Böhringer et al. (1998) warn against too optimistic estimates of total cost savings from CO_2 trading. According to their model simulations, trade would produce efficiency gains amounting to only around 10 percent of the EU-wide total abatement costs.

We study an additional interesting aspect of the cost-efficiency of trading CO_2 emissions: the overall environmental impacts of active climate policy measures. Since there are no technological possibilities to "clean up" CO_2 emissions, the measures for reducing emissions are mainly related to the use of energy. Energy efficiency can be enhanced and less carbon-intensive patterns of consumption and production promoted. Consequently, when tackling the energy system as a whole, there are other harmful emissions that will be reduced by the adoption of measures to save energy. Typical examples of such emissions are sulfur and nitrous oxides (SO_2, NO_x). The other emissions are not necessarily global, but it may still be in the national interest to reduce negative regional and local environmental impacts of air pollutants. If active climate policy is associated with considerable secondary benefits, these benefits should be taken into account in cost-efficiency considerations.

Neglecting the secondary environmental benefits of measures limiting greenhouse gas emissions brings into mind the well-known criticism earlier directed against environmental policy. A successful policy should not be "medium-specific", i.e. not only one emission should be controlled at a time, for the regulated emission load may then only be reduced at the expense of an increase in other emissions; in other words, the residuals only alter their form (Ayres and Kneese, 1969). Our point here is a mirror image of this discussion. Due to the lack of cleaning mechanisms for greenhouse gases, the focus is, quite correctly, on energy use as a whole. As a result, there will be other emission reductions that come at no additional cost, i.e. gratis. Purchasing tradable CO_2 permits seems to be the most favorable, cost-minimizing policy option, but reductions in other emissions, or local and regional secondary benefits should also be considered when evaluating the net costs of policy measures. The costs per unit of CO_2 reduction become lower, if simultaneous reductions in other emissions are acknowledged.

In the previous literature, Ekins (1995, 1996) reviews estimates of secondary benefits from several international studies and presents a possible range of SO_2 related secondary benefits in the UK.[1] He also criticizes the fact that there are relatively few calculations of secondary benefits of CO_2 reduction, which is why these have been ignored in studies assessing the (net) costs of climate policy measures. In a recent theoretical study, Rubbelke (2003) refers to the same problem of underestimation of total benefits and investigates how the secondary benefits could be taken into account when implementing flexible policy instruments.

In our paper, the empirical importance of secondary environmental benefits is related to emissions trading by using the Swedish case as an illustrative example. An interesting feature of Swedish climate policy is that Sweden has already implemented a tax on CO_2 emissions, and is one of the European countries with relatively high marginal costs for reducing CO_2 emissions. Sweden would thus be an obvious candidate for buying tradable CO_2 permits. However, by launching trade in CO_2 permits, the government's tax revenues would necessarily be transferred to factor payments abroad to finance the "imports of carbon dioxide". Therefore, imposing new taxes or charges should be considered as an alternative to balancing the government budget and financing domestic transfer payments, which are currently financed by a CO_2 tax.

The target level for CO_2 emissions for each country within the European Union has been decided in an international agreement through a negotiation process, and the target level does not necessarily correspond to a level where the marginal cost

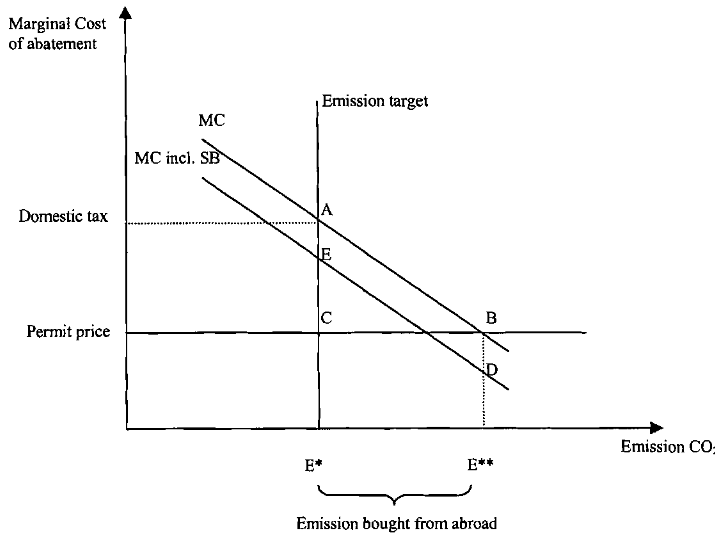
[1] See Kverndokk and Rosendahl (2000) for other studies using the same background information on benefit/damage estimates as Ekins.

of abatement equals the marginal damage for each country. As the target level is exogenously given after the completion of an international agreement, the marginal damage curve for each country corresponds to a step function. When emissions are below the target, the marginal damage is zero and when the target is hit, the marginal damage becomes infinite.

Assume now that we have two alternative instruments for reducing emissions to the internationally agreed emission target E^* (in figure 1): either reduction by a domestic CO_2 tax or an international permit trade market. In international trade with CO_2 permits, the permit price for a small country such as Sweden will be considered as given, since the proportion of total emissions (and permits traded) of a small country is very small.

If the emission constraint is achieved by a domestic tax on CO_2, the tax level is set where the marginal cost of abatement equals the emission target. However, for each emission reduction unit, there will be secondary benefits (SB) in the form of a reduction of other harmfully gases like SO_2 and NO_x, which implies that the marginal social cost including secondary benefits (MC incl. SB) is lower than the introduced domestic tax. On the other hand, if a permit market is introduced, the Swedish economy will meet a constant emission price and firms will abate until the marginal cost of abatement within Sweden equals the permit price, i.e. abate until emissions within Sweden equal E^{**}. The remaining emissions up to the emission constraint will be bought from abroad. Area ABC in figure 1 indicates the gain from introducing carbon trade, while area ABDE shows the loss in secondary benefits from emissions trading. If (ABC-ABDE) < 0, then the losses are larger than the gains and the introduction of a permit market will not be beneficial.

Figure 1.



We use a Swedish static computable general equilibrium (CGE) model, incorporating other noxious emissions (SO_2, NO_x) than CO_2 only to analyze the expected secondary environmental gains resulting from active policy measures, motivated by climate policy. To take the secondary benefits into account, we assume different estimated valuations of damage cost for SO_2 and NO_X in Sweden to reflect the willingness to pay for a marginal reduction (avoided damage) in these emissions.

The next section briefly reviews those aspects of the emissions trading literature which are relevant for our analysis. Thereafter, a short description of the model and the reference scenario ("business as usual") is given. Numerical simulations of meeting the requirements of the Kyoto Protocol with and without emissions trading are presented. Finally, the potential gains from trade in CO_2 permits are discussed with special emphasis on secondary benefits.

2. Emissions trading

The Kyoto Protocol requires that industrialized countries reduce their emissions of greenhouse gases by 5.2 percent of the 1990 levels until the period 2008-2012.[2] The Protocol allows the use of so-called flexibility mechanisms to reduce the implementation costs of the treaty. Emissions trading is one of these mechanisms.

The underlying idea of emissions trading is to allow more abatement to be undertaken where the marginal cost of abatement, at the given quota allocation, is the lowest. The purpose is to combine an administrative instrument (amount of permits; regulation target) with efficiency features of market-based instruments (emissions have a market price in terms of permit prices; taxes). In other words, the total amount of permits is determined by a quota to set an upper limit on the emissions level, but the system of trading itself guarantees cost-efficiency --- in a similar way as taxes --- such that emission reduction is reached at the lowest possible cost. Those with relatively low (high) costs of reducing emissions can benefit from selling (purchasing) permits. There will be no incentive for further trade in permits once the marginal cost of abatement from each emission equals the price of the permit.

Consequently, a fundamental incentive for launching CO_2 trading domestically or internationally is that the costs of reducing greenhouse gases differ among the sources generating CO_2 emissions. The marginal abatement costs may differ for two reasons: either the marginal cost of *abatement functions* or the emission *reduction targets* are different. For example, even if two countries have the same marginal cost of abatement functions, a cost differential arises if they have different emission reduction requirements, placing them at different points on the function. Furthermore, differences in both the marginal and the total abatement cost stem from differences in the projected population growth, the rate and nature of production growth, economic trade relations with other countries, the efficiency of the current energy technology stock, and the availability of alternative energy commodities.

The European Union has committed itself to a reduction of greenhouse gases by 8 percent from the 1990 level to the period 2008-2012, but the member countries have agreed on differentiated targets within the European "bubble". To some

[2] For a critical evaluation of the Protocol, see, e.g., Barrett (1998).

extent, the abatement cost differences were taken into account when the member countries pledged to "burden sharing" within the EU. However, the target levels agreed upon within the European Union do not necessarily harmonize the marginal abatement costs between countries. On the contrary, recent analyses indicate that countries do not face equal conditions when reducing their energy-related CO_2 emissions to meet the Kyoto targets. However, a comprehensive comparison of cost estimates is difficult because of the different assumptions underlying the different models and estimation techniques used in the analyses. Cost estimates crucially depend on the baseline scenarios assumed and the technologies included in the analyses.[3]

The International Energy Agency has estimated CO_2 mitigating costs using the energy model MARKAL (Kram 1998; Schmid and Schaumann, 1998). The marginal cost range for EU member states was estimated to be US$ 0 to US$ 252 per ton of CO_2 equivalent, if all countries cut their emissions by 8 percent from the 1990 level. When comparing the costs between the individual EU member countries, it was found that Sweden would bear a cost burden well above the average. In the US, the Clinton administration has reported that if emissions were stabilized at the 1990 levels in 2010, the implicit marginal cost would be (in terms of 1995 dollars) US$ 145 per ton of carbon, or approximately 1995 US$ 60 per ton of CO_2 (Interagency Analytical Team, 1997).

Böhringer et al. (1998) have used a CGE-model covering seven EU member countries to consider burden sharing within the European "bubble". A model illustrating a case where each country would reduce their CO_2 emissions by 8 percent from 1990 resulted in an estimate of a marginal cost range of 1995 US$ 28 to US$ 134. If trade were allowed, the market price of a CO_2 permit would be 1995 US$ 50 in 2010. Once more, to make a comparison with the US, another CGE-model result shows the marginal cost to be US$ 240 per ton of carbon (US$ 100 per ton of CO_2) if the US must satisfy its reduction target within its own geographical boundaries. The cost would drop to US$ 100 per ton of carbon (42 per ton of CO_2) with Annex I trading *and* the Clean Development Mechanism (Manne and Richels, 1998).

It is important to highlight the tentative nature of the cost projections presented in various modeling studies. A general conclusion to be drawn is that for similar

[3] The literature on the economic aspects of climate change is considerable. Here, we have considered models simulating the implementation of the Kyoto target levels. See, e.g., OECD (1998) for other CO_2 targets simulated for the US, Europe and Japan.

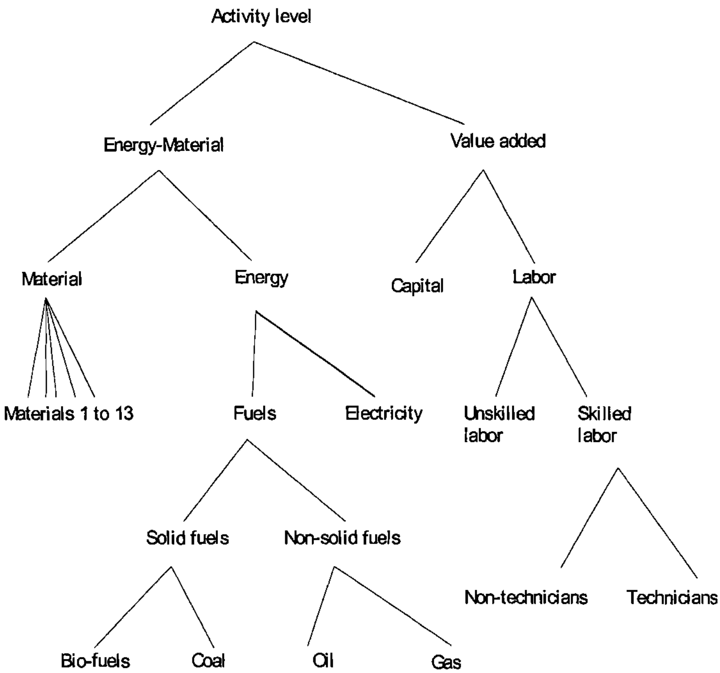
reduction objectives, the marginal costs of greenhouse gas reductions differ widely, which supports the argument that CO_2 trading would lead to efficiency gains.

3. The model and the baseline calibration

In the following analyses, we will use a Swedish general equilibrium model, EMEC[4], which has been developed to analyze environmental policy measures and their economic impacts. The model is currently calibrated for the economic and environmental accounts of 1993. The Swedish economy illustrated by the model consists of a public sector and 17 production sectors. These sectors use four inputs: capital, energy, material, and labor, where labor is divided into three groups: unskilled, technicians and skilled non-technicians. The total supply of labor is exogenous, while capital is supplied at a given international interest rate. All production factors are mobile between sectors in the economy. The production technology is captured by CES functions, and the nesting structure of input choices in production is illustrated in Figure 2. Production results in the output of 20 composite commodities, which are allocated to intermediate goods, investments and final demand. In line with the Armington assumption, domestic and foreign goods are differentiated such that non-traded and traded goods are separated. The model is closed by an exogenous Current Account ratio and the foreign price level is the numeraire. A detailed model description is given in Östblom (1999).

[4] Environmental medium term economic model

Figure 2 The input-activity specification in EMEC



The energy sector, emissions and taxes

A considerable share of air pollution is emitted from the combustion of fossil fuels: energy use and transports are emission-intense economic activities, which is why households play an important environmental role in energy political decisions. Still, heavy industries such as iron, steel and metal as well as pulp and paper, traditionally have the highest energy use per value added, as compared to other production branches in Sweden. (Statistics Sweden 1998:11)

In the model, five energy commodities are specified: electricity, coal, oil, gas, and bio-fuels. Three atmospheric emissions (CO_2, SO_2, NO_x) are linked to the production sectors, the public sector and households. It is noteworthy that the links between sectors and emissions have been established via their use of energy; the different emission contents of each type of fuel are identified using fuel-specific coefficients. Therefore, fuel substitution possibilities as a measure for minimizing emissions are relatively realistically described.[5]

The use of energy by households and firms has mainly been taxed for fiscal rather than environmental reasons. However, in addition to the direct taxation of energy, Sweden has imposed taxes on carbon dioxide and sulfur emissions: the tax rates are SEK 370 per ton of CO_2 and SEK 30 000 per ton of SO_2 [6]. When calibrating the tax rates in the model, today's reduced tax rates and exemptions for certain industries, such as the manufacturing industry, have been taken into account. There is also a charge on nitrogen oxides; large combustion plants with an annual production of 25 GWh or more pay SEK 40 000 per ton emitted. However, the nitrogen charge is neutral to the national budget, since repayments are made to operators of the plants with the lowest nitrogen emissions. Furthermore, private consumption is subject to value-added tax and other indirect commodity taxes. The government also receives income as payroll taxes paid by employers. Consequently, firms and households maximize their profit/utility by using the relatively lowest priced production factors/consumption goods, given the prevailing prices including taxes and substitution possibilities/preferences.

Reference scenario

The model reference scenario up to the year 2015 has been developed at the National Institute of Economic Research for the medium term survey of the Swedish economy (National Institute of Economic Research, 2000), and rests on the following assumptions:

- The number of employed grows by 0.4 percent per year.
- The average workweek is shortened from 36.9 hours/week to 35.5 hours/week.
- Labor productivity increases by 1.8 percent per year.
- Government expenditures increase by 1.2 percent per year.
- The Current Account surplus is slightly below one percent in 2015 and will thereby have decreased from the high levels of today.
- The world market grows by 4 percent per year.

[5] In many CGE-models, emissions are still related to aggregate output/consumption levels.
[6] Tax rates of 1997, US$ 1 = SEK 7.64 in 1997.

- World-market prices increase by 1.5 percent per year on average. More specifically, the world-market annual price increases are for: oil 1.1 percent; coal 0.6 percent; gas 2 percent; electricity 1.9 percent. The world-market price for bio-fuels is assumed to be constant during the simulation period.

Changes in the macroeconomic key variables over time, captured in the baseline scenario, are summarized in Tables 1 and 2.

Table 1. Key figures for the Swedish economy 1980-2015. Annual % change

	1980-1989	1990-1997	1980-1997	1997-2015
GDP	2.1	0.8	1.5	1.9
Private consumption	1.7	0.3	1.0	2.4
Government consumption	1.5	-0.1	0.9	1.2
Investments	3.5	-3.8	0.3	3.0
Exports	4.4	7.5	5.5	3.7
Imports	3.9	4.4	3.9	4.2
Employment [1)]	1.0	-1.1	0.1	0.2
- Private sector, total [1)]	0.9	-1.0	0.1	-0.2
- Government sector [1)]	1.5	-1.5	0.2	1.1
Current account [2)]	0.6	9.2	9.2	0.8

[1)] Hours worked
[2)] In percent of GDP in the final year
Source: SCB and EMEC

Table 2. Value added and employment 1997 – 2015. Annual percent change

Branch	Value added [1)]	Hours worked
Agriculture, fishery and forestry	0.2	-2.4
Mining	0.6	-1.9
Pulp and paper mills	1.4	-0.9
Chemical industries	1.8	-1.1
Basic metal industries	1.6	-1.4
Engineering	3.3	-0.1
Other industries	0.4	-1.7
Electricity, gas and heat supply, Water and sewage	0.9	-1.7
Petroleum refineries	0.3	-2.6
Construction	1.2	-0.2
Transportation	1.4	-0.7
Services	2.2	0.3
Real estate	0.8	0.5
Private sector, total	1.9	-0.2
Government services	1.2	1.1

[1)] Factor prices
Source: EMEC

As indicated in Tables 1 and 3, *total energy demand* is supposed to increase annually by 0.8 percent, i.e., at a lower rate than the growth of GDP, 1.9 percent. Reduced energy demand is partly achieved by enhancing the energy efficiency in the private sector. Industry and services account for almost one half of total energy consumption.

Table 3. Energy demand 1997-2015
Percent, %

	Energy demand, Annual change	Share of total energy consumption year 2015
Industry and services	0.7	48
Transportation (excluding household transports)	-0.1	11
Energy supply	1.3	13
Households	1.1	29
Total	0.8	100

Table 4 reports two alternative scenarios with a lower (1.3 %) and a higher (2.5 %) annual growth of GDP, and a corresponding growth of emissions. It is worth pointing out that no major development or breakthrough in cleaning mechanisms to reduce SO_2 and NO_x has been assumed, but the growth of emissions represents today's technological abatement possibilities.

Table 4. Alternative scenarios
Annual growth rates (%) and emission levels in 2015 (mill./1000 ton)

	GDP %	CO_2 % / mill.ton	SO_2 % / 1000 ton	NO_x % / 1000 ton
Alternative, low	1.3	0.3 / 60	0.0 / 100	0.9 / 410
Baseline	1.9	0.9 / 67	0.7 / 110	1.8 / 460
Alternative, high	2.5	1.5 / 74	1.3 / 120	2.2 / 510

One conclusion to be drawn from Table 4 is the relatively strong positive correlation between emissions and economic growth. Consequently, the general economic development behind the scenarios should be kept in mind in comparisons between the reference and policy scenarios. In the following analyses, we use *baseline* GDP growth as our reference scenario.

4. Kyoto simulations

Within the European "bubble", Sweden has negotiated a target of not exceeding the greenhouse gas emissions level of 1990 by more than 4 percent in 2008-2012.[7] The following simulations illustrate the effects of fulfillment of the Swedish CO_2 target, such that all simulation results are related to the reference scenario described in Section 3 above. The difference between the reference scenario and the alternative policy scenario ("Kyoto scenario") can thereby be interpreted as the consequence of implementing the climate policy Sweden has internationally agreed upon. It should be noted that we assume that world-market prices do not change due to the implementation of the Kyoto Protocol.

The measurement reference for the reduction in greenhouse gas emissions within the Kyoto Protocol is the average of emissions during the period 2008-2012. It should be pointed out that the simulations here have 2015 as their final year, since the reference scenario was initially prepared for the medium term survey of the Swedish Department of Finance.

Compliance with the Kyoto Protocol by reducing CO_2 emissions within Sweden

The Kyoto Protocol can be implemented in Sweden by increasing the current carbon dioxide tax, such that the use of energy in the economy decreases to a level where carbon dioxide emissions conform to the agreed level. When the tax rate is increased, economic agents have several options to adopt to the new price levels in the long run. Substitution between fuels and between fuels and other inputs makes it possible to reduce emissions without decreasing output. Our simulations show that the carbon dioxide tax must be increased approximately 2.5 times from the 1998 level, which corresponds to a tax of US$ 119/ton of CO_2 (or SEK 0.91 /kg CO_2)[8]. However, one reason for the high tax rate is the large number of exemptions applied in practice. The manufacturing industry has a reduction of 50 percent from the common carbon dioxide tax level, and carbon dioxide emissions from industry processes are not taxed at all.

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[7] The possibility to increase emissions was motivated by the Swedish decision to phase out nuclear power.

[8] Using the exchange rate of US$ 1 = SEK 7.64 and 1997 prices.

Table 5. Macroeconomic effects of the policy scenario, compliance with the Kyoto Protocol in 2015

	Percentage change compared to the reference scenario	Billion SEK compared to the reference scenario
GDP	-0.3	- 7.0
Private consumption	-0.1	-0.7
Government consumption	0.0	-0.0
Investments incl. storage	-0.5	-1.9
Exports	-0.7	-10.5
Imports	-0.5	-6.1
Real income[1)]	-0.3	-5.7

[1)] Adjusted for terms of trade effects

The difference in GDP in 2015 between the reference scenario and the Kyoto scenario (see Table 5) is 0.3 percent, or almost US$ 1 billion (slightly above seven billion Swedish crowns). This may seem a relatively small economic effect, but it should also be recalled that a static CGE model estimates the long-term cost estimate. It pertains to a situation where the economy has totally adjusted to the required changes for conforming to the emission goal, and has reached a new equilibrium. Despite the high marginal costs, a moderate impact on GDP is corroborated by other international studies.[9]

Since the supply of labor is exogenously given in the model, the level of employment is not affected by wage changes. However, the adjustment to an increased carbon tax results in modest wage reductions (less than 0.1 percent annually), which affect the allocation of labor between sectors. Moreover, since real wages decrease in the Kyoto scenario, so does households' labor income. On the other hand, the increased tax revenues from the carbon dioxide tax are redistributed to households by lump-sum transfers, which can, for example, be interpreted as a flat rate decrease in the income tax.

No employment effects can be studied in a model with given total employment and totally flexible wages. However, to test the sensitivity of employment to an increase in a carbon tax, we made an additional simulation experiment, where we assumed wages to be rigid at the reference scenario level, and where total

[9] Initially, before the agreement achieved in Kyoto, the total European costs were estimated to be 15-35 bn ECU annually by 2010 for a 15 % reduction in CO2 emissions as compared to 1990 (COM(97)481). This corresponds to 0.2 – 0.4 % of the GDP produced in the EU member countries. The MARKAL-MACRO model has been used for post-Kyoto calculations, and the estimated total costs for EU13 proved to be 0.24% of GDP. (ETSAP; Schmid&Schaumann 1998). See also Kverndokk and Rosendahl (2000) for a survey on mitigation costs for the Nordic countries.

employment will have to adjust such that demand equals supply on the labor market. This will induce a total employment effect decreasing total employment by 0.6 percent as compared to the reference case in 2015. The sectoral impacts of climate policy on the Swedish economy are illustrated in Figures 3 and 4 in both cases, i.e., with rigid and flexible wages.

Figure 3. Value added. Percentage change as compared to the reference scenario in 2015

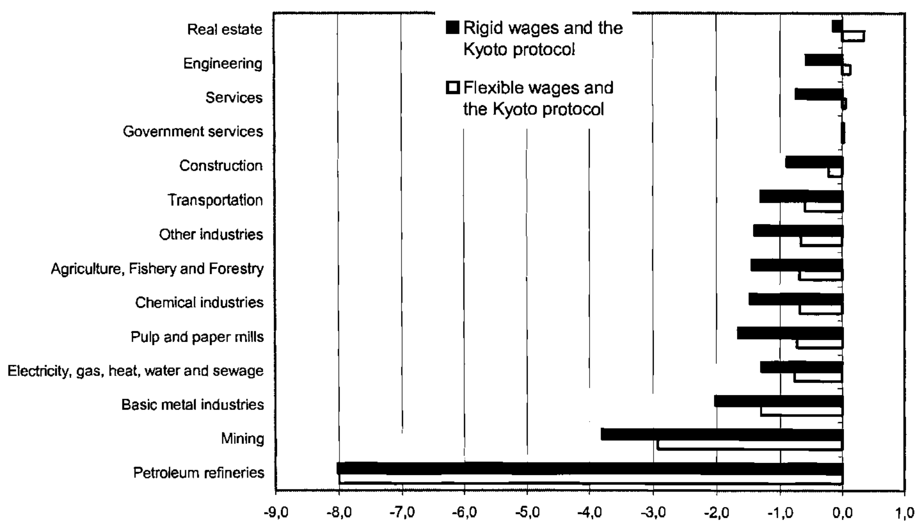
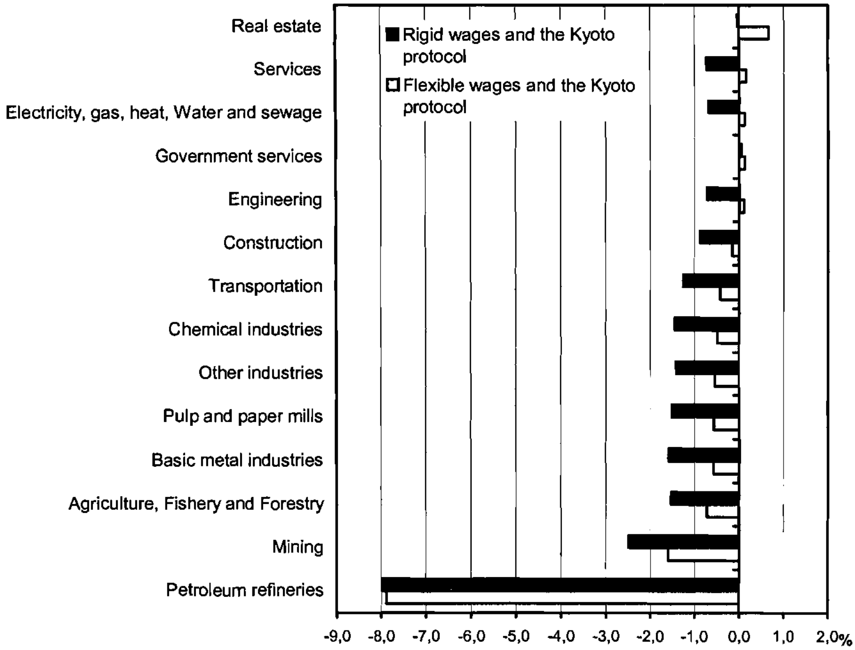


Figure 4 Employment. Percentage change as compared to the reference scenario in 2015.



Emissions trading

EMEC is a single-country model and is therefore only capable of analyzing effects on the Swedish economy. The price of emission permits must be taken as given to analyze emissions trading. This is probably also true in reality, because Sweden is a small open economy and can hardly affect the world markets, or the prices of tradable permits. Since Sweden already has a carbon dioxide tax and the tax revenues are used to finance government expenditures, the government must take its budget constraint into account. In our policy scenario, the budget constraint corresponds to that of the reference scenario.

Technically, the emission permits are modeled as imported goods bought by the government. The government, in turn, collects taxes to finance the trade on emission permits. The implementation of the Kyoto Protocol increases the tax rate in Sweden, so that it matches the international price of emission permits. When the tax rate is higher than the price of permits, it is cheaper to buy emission permits from abroad. However, the present tax system with exemptions to certain industries means implicit subsidies for the exempted industries, whenever the price of internationally tradable CO_2 permits is higher than the reduced (exempted) domestic tax. In this case, the government must finance its increase in expenditure by decreasing the households' consumption possibilities, which can be interpreted as an increase in income tax or as a decrease in government transfers to households.

There is considerable uncertainty about the future international price level of CO_2 permits. We have chosen to illustrate the effects of emissions trading with two ad hoc price levels for international emission permits, US$ 100/ton of CO_2 and US$ 50/ton of CO_2, the latter approximately corresponding to the current Swedish carbon tax rate.

Table 6. Effects of the implementation of the Kyoto Protocol as compared to the reference scenario in 2015. Macroeconomic effects (rows 1-8) in *billion Swedish crowns*

	No International Trade	Trade with Emission Permits Price: $50	Trade with Emission Permits Price: $100
GDP	- 7.0	-3.9	-6.8
Private consumption	-0.7	-0.4	-0.5
Government consumption	-0.0	0.0	0.0
Investments incl. inventories	-1.9	-0.1	-1.4
Exports	-10.5	-0.1	-7.9
Imports[1)]	-6.1	-0.3	-4.6
Real income[2)]	-5.7	-0.5	-4.1
Total costs of emission permits	0.0	3.6	1.7
CO_2 –emissions *in million tons* compared to the reference scenario	-9.1	-1.2	-7.1
Percent of the total CO_2-reduction bought from abroad.	0.0	97.2	22.8
Carbon dioxide tax within Sweden, *US$/ton*	119	50	100

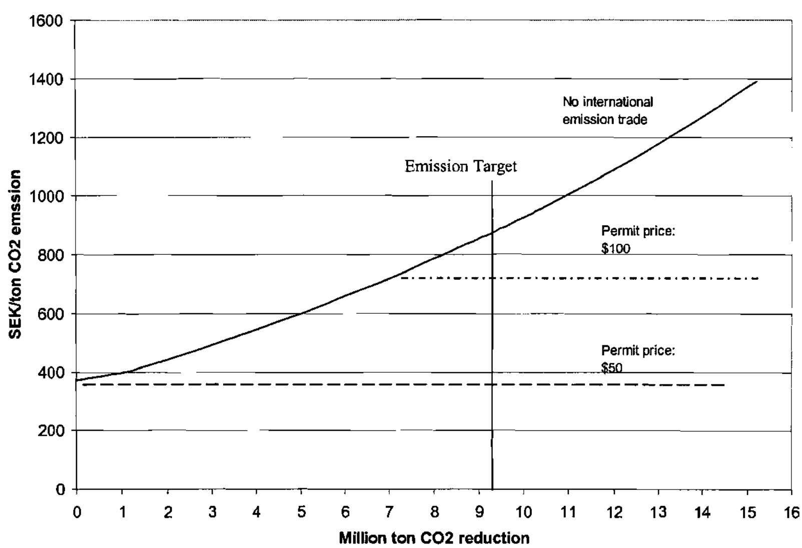
[1)] Does not include imports of emission permits.
[2)] Adjusted for terms of trade effects

Allowing international trade with emission permits at the above given prices, the macroeconomic effects of the Kyoto Protocol become even more negligible than in the case of reducing carbon dioxide emissions entirely within the Swedish borders. When the price of the emission permit is 50 dollar per ton of carbon dioxide, the present emission tax is only slightly increased to reach the 50 dollar level (from the present level of 48 dollar per ton of CO_2). The domestic carbon dioxide emissions do not increase to any considerable extent, and the reduction needed to meet the Kyoto Protocol is bought abroad. The carbon dioxide tax revenue used for financing government expenditures in the reference case is now used for financing the emission permits bought abroad. This leads to a decrease in the transfer payments to households, but since GDP grows faster, the negative effects on private consumption are very moderate and, in total, smaller than in the case of no international trade (second row in Table 6).

Importing emission permits naturally affects the current account, which is exogenously given as a percentage of GDP. In the long run, the government cannot "borrow" from abroad to finance its imports. Instead, all imports must be financed by exports and the balanced current account constraint must be satisfied in the final year of the simulation period. The permit payment is an expenditure flow out of the country. Consequently, as can also be seen from Table 6, exports are not decreased as much as the imports of goods and services in the scenarios with emissions trading.

If the price of emission permits is 100 dollars per ton of CO_2, the difference in GDP is hardly noticeable as compared to the scenario where the emission reduction was entirely domestic. The carbon dioxide tax is raised until it reaches 100 dollars per ton of CO_2, which is only 19 dollars less than the tax needed to reach the Kyoto target within Sweden. The marginal cost curves in Figure 5 illustrate the effects of different emissions trading assumptions.

Figure 5. Marginal cost curves for Sweden 1) 2)



1) The Swedish CO2 tax was SEK 370 per ton in 1998.
2) When emissions trading is allowed, internationally determined permit prices represent Backstop technology costs for Sweden (dashed lines).

5. Taking into account the secondary benefits

Emissions of other environmentally harmful gases such as sulfur and nitrogen oxides are indirectly affected by the implementation of the Kyoto Protocol, since these gases are also strongly related to the burning of fuels. In particular, the Swedish parliament has defined 15 different domestic environmental targets that should be reached within a generation. Among other things, the goals aim at alleviating acidification and eutrofication. There is both environmental and political pressure to reduce air pollutants such as SO_2 and NO_x. Contrary to CO_2, sulfur and nitrogen emissions can be abated by various cleaning mechanisms (filters etc) and other technical solutions. However, especially for NO_x, it is fairly difficult to control emissions with an economic instrument such as an NO_x tax due to difficulties in measuring emissions. In Sweden, there exists a charge system for large NO_x emission sources, but it only controls about 5 percent of total emissions. Therefore, it is interesting to study the effects of international CO_2 trading on the reduction of other emissions; see Table 7.

Table 7. Emissions in alternative scenarios
Changes in % (and mill. /1000 tons) as compared to the reference scenario in 2015

	CO_2 % (mill. ton)	SO_2 % (1000 ton)	NO_x % (1000 ton)
No international trade	-13.6 (-9.1)	-9.3 (-10.1)	-14.5 (-69.0)
Trade with Emission Permits Price: $50	- 1.7 (-1.2)	-0.3 (-0.3)	-0.4 (-1.9)
Trade with Emission Permits Price: $100	-10.5 (-7.1)	-7.2 (-7.8)	-11.1 (-52.9)

The results show that the reductions in SO_2 and NO_x emissions are very low when the price of a tradable CO_2 emission permit is $50 per ton of CO_2, as compared to the reference scenario.[10] Furthermore, if Sweden's goal were to reduce its emissions of SO_2 and NO_x, such that they correspond to the alternative scenario

[10] There are two caveats that should be borne in mind. In our simulations, no explicit new avoidance mechanisms are included, but the emission contents of fuels are fixed. In addition, the Swedish sulfur and nitrogen oxide emissions to some extent affect other countries, and other countries export emissions to Sweden's territory. These emission transports are not included in the analysis.

of "no international trade", this would imply that the emissions of SO_2 should be decreased by 9856 tons and the emissions of NO_x by 67144 tons. How these "extra" emissions should be valued in monetary terms is very uncertain, but a few Swedish studies exist that give estimates for the damage costs caused by emissions of SO_2 and NO_x. The valuation estimates of damage costs are assumed to be constant. This assumption rests on the argument that the marginal damage of emissions is likely to rise with emissions, rather than the reverse, so that the assumption of linearity of the damage function can be taken to yield a lower bound in the estimate of the benefits of emissions abatement at emissions levels equal to or higher than the present ones.

Another principle that we use is to evaluate these emissions according to their present tax rate. Given that both SO_2 and NO_x emissions increase in the reference scenario for 2015, their present Swedish tax rates should give a lower bound estimate on the marginal benefits of reducing these pollutants, or avoiding their damages.

Table 8. Total cost of international trade with permit price \$50.

	Valuation estimate of damage costs SEK/kg SO_2	Valuation estimate of damage costs SEK/kg NO_x	Total cost of SO_2 and NO_x relative to no international trade scenario Billion SEK	Total cost of CO_2 emission reduction incl. secondary emissions. Billion SEK
According to present tax level	30	40	-3.0	-6.9
SAMPLAN 1996:3	16	100	-6.9	-10.8
SIKA 1999:6	20	60	-4.2	-8.1

The tax rates are SEK 30 000 per ton of SO_2 and SEK 40 000 per ton of NO_x, so that an estimate of the total damage of both SO_2 and NO_x using the emission taxes is SEK 3 billion. In other words, this is the value of the SO_2 and NO_x emission reduction lost when the CO_2 reduction is not carried out within Sweden. If this damage estimate (approximately SEK 3 billion) is added to the loss in GDP (SEK 3.9 billion), the total cost of fulfilling the Kyoto Protocol by engaging in international trade at a price of 50 dollars per ton of CO_2 emission is SEK 6.9 billion. This indicates that the obvious gain from international trade has almost vanished if the secondary benefits are taken into account in the calculations. The two alternative valuations according to SAMPLAN 1996:3 and SIKA 1999:6 have higher valuation estimates for NO_x, but lower ones for SO_2. The total damage cost estimate is, however, larger compared to the valuations based on the present tax level. In these two cases, the total cost including the loss of secondary benefits will exceed the total cost in the no international trade scenario. In other words, if secondary emissions are taken into consideration, the gain from emissions trading (lower GDP reduction) relative to domestic reduction is turned into a loss as compared to domestic reduction.

The same calculations can be performed for the scenario where the emission price is US$ 100 per ton of CO_2. In this case, the SO_2 emissions must decrease by 2314 tons and the NO_x emissions by 16147 tons to correspond to the emissions levels in the case of no trading.

Table 9. Total cost of international trade with permit price $100.

	Valuation estimate of damage costs SEK/kg SO_2	Valuation estimate of damage costs SEK/kg NO_x	Total cost of SO_2 and NO_x relative to no international trade scenario Billion SEK	Total cost of CO_2 emission reduction incl. secondary emissions. Billion SEK
According to the present tax level	30	40	-0.7	-7.5
SAMPLAN 1996:3	16	100	-1.7	-8.5
SIKA 1999:6	20	60	-1.0	-7.8

Our three different valuations of SO_2 and NO_x lead to the same main result. After adding the total damage cost of the secondary emission to the GDP loss, the total cost for Sweden of meeting the Kyoto target by allowing international trade at US$ 100 per ton of CO_2 is higher than in the no international trade scenario. In other words, taking into account the damage costs, the total economic costs of complying with the Kyoto Protocol, when emission permits cost US$ 100, are higher than if emissions were reduced just within the country.

The conclusion from our model calculations and estimates of the damages of SO_2 and NO_x emissions is that taking secondary benefits into account may affect the attractiveness of emissions trading when the effectiveness of environmental policy as a whole is an issue. A word of caution is in order here because of the uncertainties regarding the development of abatement technology for SO_2 and NO_x emissions. Potential technological developments in abatement have not been included in our model for the very reason that forecasting future technological development is obviously very difficult. Moreover, we used constant, current environmental tax rates as one of the damage estimates for pollution. This is a justified assumption, if we believe the tax rates to be optimal as well as firms being rational and cleaning emissions today, as long as the abatement costs are lower than the taxes. It is also a standard assumption that instead of being constant, the marginal benefits of abatement tend to decrease with abatement. That is why our damage estimates would be rather conservative measures, and give a relatively strong support to the importance of secondary benefits when emissions tend to increase. However, the marginal abatement costs may decrease over time, due to technological development, which would affect the optimal taxes.

6. Conclusions

International emissions trading is a textbook example of an efficient way of reducing global pollutants such as CO_2 emissions. However, some writers emphasize cases when CO_2 trading as such does not necessarily guarantee an efficient emission reduction. In this paper, we have considered another critical argument, i.e. secondary benefits. If there are other important environmental goals than only reducing CO_2 emissions related to energy use and combustion of fossil fuels, the reduction of carbon content in the atmosphere has positive by-effects that should be taken into account.

In a CGE-modeling framework, we have analyzed the Swedish environmental goals conforming to the Kyoto Protocol, when simultaneously meeting national goals to alleviate acidification and eutrofication effects by reducing SO_2 and NO_x pollutants. We have found that when secondary benefits of measures aiming at reducing CO_2 are taken into account, it may still be in the government's interest to nationally decrease CO_2, instead of engaging in seemingly low-cost trading.

Two counter arguments for our reasoning is also evident. First, if effective policy instruments for tackling *all* emission gases resulting from the burning of fossil fuels exist, there would be no relevance for the secondary benefit argument. In this case each emission would be reduced by its specific policy instrument, i.e.

there would be one instrument for each emission gas, and the introduction of carbon dioxide emission trading would probably be welfare improving. However, we argue that there are difficulties in using economic policy instruments for *all* emission gases related to the burning of fossil fuels due to measurement problems. Therefore, secondary benefits must be taken into consideration when evaluating the cost of a carbon policy.

Second, since SO_2 and NO_x emissions do not obey national territorial borders (in a similar way to that of CO_2 emissions), the emission reductions elsewhere also benefit the country buying CO_2 permits. However, this is not our point. Lack of data prevents us from studying, e.g., the effects of diminished benzene emissions (in addition to sulfur and nitrogen) due to decreased fuel consumption in national transports, which contribute clearly and, for the major part, *only* to local environmental benefits. Here, sulfur and nitrogen emissions have been used as an example of the secondary benefits phenomenon, since there are relatively reliable data on these emissions. The point of the paper is that there may also be rational reasons for engaging in efforts to domestically reduce carbon dioxide emissions, when no cleaning technology is available and tackling an initially very specific environmental problem leads to measures (such as energy saving) also affecting other emissions.

Our simulations have been based on the actual Swedish tax structure, including carbon dioxide tax. Therefore, we have also investigated how a switch to an abatement policy of "importing" CO_2 reductions affects private and government consumption. We could not find any negative effect, simply because CO_2 taxes still today constitute such a small share of the total tax base and the government budget.

Our conclusion is that more research efforts should be directed to the benefit side in the search for efficient abatement targets and strategies. Seemingly irrational or inefficient environmental policy should not be condemned without a careful investigation of the total benefits of the policy measures. In reality, specific measures, focused on solving a certain environmental problem, often have economic and environmental “spillover” effects. Here, we have emphasized that the spillover effects can also be positive, which should affect the net cost-efficiency considerations of environmental policy.

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Equity in International Agreements on Greenhouse Gases*

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III

Abstract

I use a multi-regional computable general equilibrium model (GTAP-EG) to assess the economic consequences of initial carbon dioxide permit allocations. I compare ad hoc approaches, like "Ability to pay", "Sovereignty" and "Egalitarian", with those resulting from specifying a social welfare function. My main conclusion from these simulations is that the choice of social welfare function is of importance. Contrary to earlier literature, I find that the initial distribution not only gives second-order effects but affects equilibrium prices and therefore income.

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1. Introduction

According to the Kyoto protocol (UNFCCC 1998) a particular group of countries is obliged to reduce the greenhouse gas emission levels to a country-specific target, which must be fulfilled in the period 2008-2012. These targets are the fruit of negotiations and full of country-specific compromises. The negotiation outcome raises three main questions. First, is the total reduction target for the world at the "right" level? Second, can the emission target be efficiently achieved? And third, in what sense is the emission target equitable?

The first two questions have been thoroughly studied in the economic literature with both analytical and numerical tools (e.g. Nordhaus 1994 and Weyant el al. 1999). While the question of equity is mentioned in the discussions, it is not as intensively studied, although equity considerations are of considerable practical importance in the Framework Convention on Climate Change. Countries are less likely to fully participate in international agreements if they do not perceive the arrangements to be "fair". Banuri et al. (1996) argue that "the issues of how future emissions should be allocated, and who should pay for abatement, form some of the most contentious equity issues in the climate policy. In the absence of separate international transfers associated with abatement, the initial distribution of emission constraints will largely determine the distribution of costs".

Numerous rules for allocating the permits have been presented in academic articles (e.g. Rose 1992) and in connection with the work done by the Intergovernmental Panel of Climate Change. There is a tendency that each country proposes an allocation rule based on self interest. For example, Russia suggests that the allocation of carbon permits should be based on land area as a proxy for carbon sinks, which would obviously favor large countries such as Russia itself. Iceland, on the other hand, suggests that the allocation should at least partly depend on the amount of alternative energy resources, which favors countries like Iceland. In other words, it is difficult for the parties involved in the international negotiations to look beyond self-interest. My suggestion is that welfare theory could be used as an alternative to the ad hoc rules. Welfare theory tells us how to add individual countries' welfare into a social welfare function, which incorporates the prevailing equity judgments in society. Maximizing social welfare with respect to the initial allocation of carbon permits, an "equitable" allocation of initial permit rights is formed. Compared to the more ad hoc rules such as per land area, ability to pay or historical emissions, this allocation builds on a transparent theory. Naturally, the choice of which social welfare function to use is not an objective problem.

As pointed out in Banuri et al. (1996), the climate change literature at that time had never used welfare theory to find the initial allocation of carbon permits. Since then, however, a few authors have used this theory to study related issues such as equitable cost-benefit analysis, e.g. Azar 1999; Azar and Sterner 1996 and Tol 2001, 2002. These studies do not focus on the initial allocation of permits, given a total emission target, but how to find the total emission target considering equity. Tol (2001) uses an integrated assessment model of climate change called FUND to consider three different approaches for simultaneously studying equity and efficiency. One of these methods is to maximize a global welfare function explicitly including distaste for inequity. His conclusion is that the higher is the distaste for inequity, the lower is the emission target (more reduction) for the world, since the costs of greenhouse gas emission reduction by the richer regions count less and less for the higher distaste of inequality, while the avoided damages of climate change to the poorer regions count more and more. In this study, however, my interest is not in the differences in weights of damages and costs, but how the welfare weights influence the equitable allocation of initial permit rights and how this affects the different economies within the agreement. I find different allocation rules to not only imply distributional effects, but also income effects. This income effect drives me to look at the equitable cooperative solution, since real income effects should influence the social optimal level of emissions. In other words, the welfare weights do not only influence how to weigh damages and costs, since there is an additional effect through changes in real income.

This paper will give special attention to the Swedish results. Sweden is a small open economy with relatively low emission per capita and per GDP (relative to other OECD countries). Within the Kyoto protocol, Sweden is part of the European bubble and was allowed to increase its emission of greenhouse gases by four percent from the 1990 emission level until the period 2008-2012. In Marrakech, Sweden voluntarily chose to strengthen its target to minus four percent, and there is still an ongoing debate in Sweden about reducing the country target even further. Some politicians have suggested a target as low as minus eight percent below the 1990 emission level.

The structure of this paper is as follows. The next section briefly reviews some of the literature on the ad hoc rules. Section 3 presents equity rules based on economic welfare theory, while section 4 addresses the economic implications of both ad hoc rules and rules based on economic theory. In section 5, a damage cost function is introduced and the cooperative solution with distribution weights is found. The final section concludes and summarizes.

2. Ad hoc equity weights

Several articles have numerically studied different equity rules not related to welfare theory (e.g. Barrett 1992; Grubb 1989; Kverndokk 1992 and Rose et al. 1998). Typically, they take the papers by Rose (1992, 1990), which put forward a number of ethical criteria, as their starting point. These criteria are summarized in table 1. Rose does not single out a preferable rule but other authors have more explicitly stated their viewpoint. Grubb (1989) and Kverndokk (1992) advocate an allocation according to population, pegged to a base period. Barrett (1992) has put forward a "Kantian" rule, according to which countries must abate at least as much as they would wish the others to do.

Table 1. Equity criteria for global warming policy

Criterion	General description	Distribution of permits: operational rule	Distribution of permits: reference basea
Horizontal	Persons in the same group are equally treated	Equalize net welfare change (net cost of abatement as a proportion of GNP) across nations	GNP, (land area, energy reserves, CO_2 emissions)
Vertical	Greater concern for the disadvantaged	Progressively distributed permits (net costs inversely correlated with per capita GNP)	GNP, (land area, energy use, energy reserves, CO_2 emissions)
Ability to pay	Parties pay according to their means	Equalize abatement costs (gross costs as a proportion of GNP) across nations	GNP
Sovereignty	Each nation/person is guaranteed a minimum of basic rights and resources	Cut back emissions proportionally across nations	CO_2 emissions
Egalitarian	Treat every human being equally	Cut back emission in proportion to population	Population
Market justice	Free market is a fair means of allocation and distribution	Auction entitlements to highest bidder	--
Consensus	A decision is fair if the parties agree to it	Distribute permits so that a majority of nations is satisfied	(population)
Compensation	Pareto rule: no party should be made worse off	Distribute permits so that no nation suffers a net loss of welfare	GNP, (energy reserves)
Rawl's Maximin	Maximize the welfare of the worst off nations	Distribute large proportions of permits to the poorest nations	GNP
Environmental	Emphasizes primacy and "rights" of ecosystems	Cut back emission to maximize environmental values	CO_2 emission, (energy use, land area)

a) Parentheses indicate that the applicability is weak.
Source: Rose (1992).

Reiner and Jacoby (1997) summarize some of the proposals for emission reduction by industrialized countries presented by parties to the Framework Convention on Climate Change (FCCC) in the Ad-Hoc Group on the Berlin Mandate (AGBM). These suggestions represent criteria on a political agenda while Rose's (1992) criteria are based on an "objective" academic agenda. Naturally, the suggestions on the political agenda are in most cases variations of the suggestions in Rose (1992). However, there is a clear tendency that each country makes suggestions favoring its own position. This is apparent in table 1 in Reiner and Jacoby (1997), here given as table 2.

Table 2. Sample of Differentiation Proposals Submitted to AGBM

Country	Differentiation Criteria
France and Switzerland	Per capita carbon emission in 2000
Australia	Equal percentage change in per capita economic welfare taking into consideration: Projected Population growth Projected real GDP per capita growth Emission intensity of exports Fossil fuel intensity of exports Emission intensity of GDP
Poland et al.	GDP per capita Contribution to global emissions Emissions per capita and/or emissions intensity of GDP
Norway	Emissions intensity of GDP GDP per capita Emission per capita
Island	Emissions intensity of GDP GDP per capita Emission per capita Share of renewable ton total energy
Uzbekistan	GDP per capita
Estonia	GDP per capita Responsibility for global warming
Iran	GDP Historical share Dependency on income from fossil fuels Access to renewable Defense budget Population growth Special circumstances Share in international trade
Brazil	Relative historical responsibility
Russian Federation	Land area (as a proxy for sinks) Contribution to global reduction efforts

The different proposals in table 2 clearly show the difficulties in reaching an international agreement. The outcome for one country might be quite different, depending on the chosen criteria. Reiner et al. (1997) review the definitions of responsibility and equity supposed to underlie the proposals. They conclude that a sufficient number of legitimate arguments exist, such that different countries can readily attach a philosophical label to any position that happens to align with their economic interests. Not surprisingly, this implies that there is no easy way of finding a proposal satisfying all parties.

In welfare economics, this problem can be addressed using a social welfare function representing a social decision-maker's preferences about how to trade off the utilities between different agents. The prevailing equity judgments in society are reflected by the social welfare function and if social welfare is optimized under the constraint that a certain emission target must hold, the result will be "equitable" and Pareto optimal.

3. Utility, social welfare function and the equitable allocation of permit rights.

As a first step, the preferences of individual countries (utility function) and those of the group as a whole, i.e. the social welfare function, must be defined.

Country welfare

Utility for country i is taken to be a function of consumption, C_i. If country i participates in an international agreement to reduce carbon dioxide, consumption will depend on the level of carbon dioxide emitted in country i, E_i. The utility function can be defined in the following way:

$$u_i = u_i(C_i) \text{ where } C_i = C_i(E_i). \tag{1}$$

In sections 3 and 4, I have disregarded the fact that utility may depend on the quality of the environment which, in turn, depends on the stock of emissions. Utility is simply a function of emissions affecting the production possibilities.

A social welfare function of Bergson-Samuelson type $W(u_1, u_2, \ldots u_n)$ expresses society's judgments on how individual utilities are to be compared to produce an ordering of possible social outcomes, i.e. society's view on equity and fairness is assumed to be reflected in W, through an appropriate choice of functional form[1]. Making these assumptions involves strong value judgments. However, if policy

[1] Mas-Colell et al. 1995

makers are not willing to make such value judgments, little can be said about aggregated social welfare.

Assume no international permit trade to be allowed. A carbon permit system is set up within each country to fulfill the target set on that country (handles efficiency within the country). Who should emit is then determined through the maximization of the social welfare function, which will put equitable judgments on the issue of who should emit

$$\max_{E_1, E_2 \dots, E_n} \quad W = W(u_1, u_2, \dots\dots u_n) \quad s.t. \quad \sum_i E_i \le E_{tot} \quad and \quad E_i \ge 0 .$$

The constrained social optimum is:

$$\frac{\partial W}{\partial u_i}\frac{\partial u_i}{\partial C_i}\frac{\partial C_i}{\partial E_i^*} = \frac{\partial W}{\partial u_j}\frac{\partial u_j}{\partial C_j}\frac{\partial C_j}{\partial E_j^*} \qquad i \ne j \tag{2}$$

$$\sum_i E_i^* \le E_{tot}$$

$$E_i^* \ge 0 .$$

The weighted change in consumption due to an initial change in distribution should be equal across countries. The weights correspond to the marginal social utility of income and will depend on the choice of welfare function and utility function.

If there exits a perfect permit market within each country and utility is maximized subject to the emission constraint, the marginal cost of abatement in country *i* equals the carbon permit price, P_i^{permit}, in country *i*

$$\frac{\partial u_i}{\partial C_i}\frac{\partial C_i}{\partial E_i} = P_i^{permit} ,$$

i.e. an "equitable" distribution of emission rights, based on welfare theory, should follow the rule: the permit price weighted by marginal social utility should be equal across all countries within the international agreement.

3.1 Equity weights and the choice of utility and social welfare function

The choice of welfare and utility functions consists of value judgments, as previously discussed. In this study, I test three special cases of the general welfare function, $W = \sum_i \frac{1}{1-\rho} u_i^{1-\rho}$, to show how different equity judgments affect the results. Parameter ρ reflects the distaste for inequality. The higher is ρ, the more W is determined by the welfare of the poorer countries.

1. Utilitarianism
   If $\rho = 0$, the social planner is willing to renounce one unit of country *i*'s utility for a gain of one unit of country *j*'s utility. This holds, regardless of the degree of inequality: the social planner is completely indifferent to the degree of inequality between countries.
2. Bernoulli-Nash welfare function (Cobb-Douglas)
   The Bernoulli-Nash welfare function, $\rho \to 1$, is the product of countries' utilities. This indicates that a social planner with these value judgments strives at equalizing differences between countries.
3. Rawls' utility function[2]
   An extreme version of the social welfare function arises when $\rho \to \infty$. This function is associated with Rawls (1971) and indicates that the welfare of society only depends on the utility of the poorest country.

An often used utility function in welfare economics is the iso-elastic utility function[3] which solely depends on consumption. This functional form will also be used in this paper. Equation (3) is the iso-elastic utility function where (1-e) is the income elasticity of marginal utility[4]

$$u_i = \frac{1}{1-e_i} C_i^{(1-e_i)}. \tag{3}$$

[2] This utility function will only be used in section 4.3.
[3] According to Boadway and Bruce 1984 pp. 279.
[4] The income elasticity of marginal utility is not invariant to monotone transformations of *u*.

The equity weights for the different assumptions regarding social welfare and utility function are summarized in table 3.

Table 3. Equity weights for the different social welfare functions

Social welfare function		Equity weights
$W=\sum_i \frac{1}{1-e} C^{1-e}$	Utilitarian	1
$W=\min\{u_1,u_2,\dots,u_n\}$	Rawls	Max the poorest nation's utility with respect to emission.
$W=\prod_i (C_i)$	Bernoulli-Nash	$\frac{1}{C_i}$

4. Simulations

The aim of this section is to test how different distributions of initial carbon permits, based on different social welfare functions, affect the results of the Kyoto protocol. As mentioned earlier, I will also test some ad hoc rules not based on economic theory for comparison.

A Computable General Equilibrium model, GTAP-EG model[5] is used to study the result of the choice of equity weights. Section 4.1 presents the model; for a detailed algebraic description see Paltsev (2000).

4.1 The GTAP-EG model

The GTAP-EG model is built around two databases, the Global Trade Analysis Project (GTAP) database and energy statistics from the International Energy Agency (IEA). The GTAP dataset (version 4) represents global production and trade for 45 regions, 50 commodities and 5 primary factors in 1995. The IEA data provide a description of global energy flows. Together with energy prices and energy tax information, it is possible to construct a consistent benchmark dataset representing the benchmark equilibrium in the core GTAP-EG model. The resulting integrated economic-energy dataset allows for a disaggregation level of 45 regions, 23 goods (including 5 energy goods) and 5 primary factors.

[5] Model by Rutherford and Paltsev 2000 with some extensions regarding carbon permit trading to fit the analysis of this paper.

The model structure is as follows. Primary factors include labor, capital and fossil fuel resources. Labor and capital do not move across regions, but are intersectorally mobile. A sector-specific resource is used in the production of primary fossil fuels (crude oil, coal and gas), resulting in an upward sloping supply schedule for those goods. The production of commodities other than primary fossil fuels is captured by aggregate production functions characterizing technology through substitution possibilities between various inputs.

Nested constant elasticity of substitution (CES) cost functions with three levels is employed to specify the capital-labor-energy-material (KLEM) substitution possibilities in domestic production. At the top level, non-energy inputs are employed in fixed proportions with an aggregate of energy, capital and labor. The material input of good i in sector j corresponds to a CES Armington aggregate of non-energy inputs from domestic production and imported varieties. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. Finally, at the third level, capital and labor trade are substitutable at a constant elasticity of substitution.

The model allows sufficient levels of nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy, i.e. electricity. In the production of fossil fuels, labor, energy and material inputs are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil-fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with exogenously given price elasticities of fossil fuels supplies.

Final demand in each region is determined by a representative agent maximizing utility subject to a budget constraint with fixed investment (i.e. given the demand for the savings good). Total income of the representative household consists of factor income and taxes. Final demand of the representative agent is given as a CES composite combining consumption of energy aggregate and a non-energy consumption bundle. Substitution patterns within the non-energy consumption bundle are reflected via Cobb-Douglas functions with an Armington aggregation of imports and domestic commodities. The energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution. All commodities, except electricity, are internationally traded. For all commodities, the Armington assumption of production differentiation is adopted.

I have made small changes to the model by extending it with the possibility to trade internationally with emission permits between counties. As noted, the original database has 45 regions, 23 goods and 5 primary factors. The model used in my simulations has 6 regions, 23 goods and 3 primary factors.

4.2 Linking the GTAP-EG model to the discussion in section 3.

In the GTAP-EG model, the utility function is specified as $u_i = C_i$, where C_i is total aggregate consumption (C_i is a CES function of the different consumption goods and services). However, any positive monotone transformation of the utility function will not affect the result of the model. Hence, without any loss of generality, I assume that $u_i = \frac{1}{1-e} C_i^{1-e}$, where 1-e is the income elasticity of marginal utility. Values of the income elasticity of marginal utility between 1 and 1.5 are commonly used in the literature (see e.g. the discussion in Cline 1992), but there are some studies which note that the income elasticity of marginal utility may be as low as 0.8 (see Pearce and Ulph 1992). I have chosen to present results when assuming the income elasticity of marginal utility to be one[6].

The model aggregates the world into six regions: OECD-America (excl. Mexico), OECD-Pacific (excl. South Korea), OECD-Europe (excl. Sweden), Sweden, Central and Eastern Europe and the former Soviet Union, and finally the last region aggregates the remaining countries of the world.

The results of the simulations should (as far as possible) be independent to the aggregation of regions. The equity weights, based on welfare theory, must therefore be calculated as per capita consumption and not purely consumption, otherwise the result will hinge on the choice of regional aggregation (the size of each region). However, some regional dependency will still exist in these simulations, due to the fact that each region will set up a CO_2 permit market to fulfill its emission constraint. In other words, there will be a permit market for carbon emissions within each region, but not between regions (if not otherwise stated). Regional markets for permits seem realistic at this date, since the coordination and administrative problems of an Annex 1 wide permit market are large and difficult to finalize before the final period of the Kyoto agreement. What is observed is the

[6] I have performed simulations for elasticities as high as 1.5 and down to 0.5. This does influence the quantitative result, but does not change the qualitative results.

preparation for permit markets within regions, for example the EU permit system (COM (2001)581).

4.3 The reference scenario.

The emission targets within the Kyoto protocol must be fulfilled during the period 2008-2012. The final year in these simulations is set to the year 2010 and, in a reference scenario, I predict how the economies would evolve if no emission targets were imposed.

The reference scenario approximately replicates the International Energy Organizations 2010 (International Energy Organization 2000) forecast for GDP and CO_2 emissions in each region of the model. GDP is assumed to be growing at about two percent in most OECD countries, slightly more in some countries. The Former Soviet Union and Eastern European countries grow at about 1.5 percent per year. The countries aggregated into the region "The Rest of the World" have a much larger growth rate, up to 4 percent. The projection for the use of fossil fuels implies that gas will increase by more than twice as much as the increase of oil and coal, which indicates a shift to less carbon-intense fuel. However, the projection of coal and oil use still suggests a substantial increase during the period in question. Table 4 summarizes the benchmark scenario.

Table 4. Benchmark scenario. Yearly percentage change 1995-2010

	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3] (excl. Sweden)	Sweden	Former Soviet Union and Eastern Europe[4]	Rest of the World
GDP	2.6	2.1	2.2	2.2	1.5	4.1
Welfare	2.8	2.4	2.3	2.6	1.5	4.4
CO_2 emission oil	1.7	1.4	0.3	0.3	1.9	2.6
CO_2 emission gas	1.9	1.9	4.4	4.3	2.8	6.7
CO_2 emission coal	1.5	0.7	0.0	0.0	-0.4	3.5
CO_2 emission total	1.7	1.3	1.3	0.4	1.5	3.6

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

The sectors of the economy will approximately follow the growth of GDP in the different regions. I have not systematically evaluated the sensitivity of my results to assumed growth-paths, although this would be a useful extension. However, such an analysis is not so relevant for this study since I merely want to point out the differences in results because of the choice of equity weight.

4.4 Simulation results based on different distribution rules.

The emphasis of the results presented in this section lies on the analysis of the potential impacts of alternative equity rules given a particular emission target; in this case the Kyoto protocol. The target roughly involves a 5% reduction in the developed countries to the final year 2010, based on the 1990 emission level. This reduction is translated into the model framework and will only consider CO_2 emissions.

The different definitions of equity outlined in sections 2 and 3 will result in different rules for the initial distribution of CO_2 permit rights. Table 5 shows the initial emission distributions, depending on the choice of social welfare function and the ad hoc equity rules.

Table 5. Initial emission distribution.
Percentage change relative to 1990 (base year of the Kyoto protocol).

Distribution rule	OECD-America[1] [5424][6]	OECD-Pacific[2] [1423][6]	OECD-Europe[3] [3344][6]	Sweden [55][6]	Former Soviet Union and Eastern[4] Europe [4071][6]
Kyoto distribution	-7	-3	-8	-4[5]	-2
Utilitarian	8	16	4	5	-39
Bernoulli-Nash	-9	2	-5	0	-4
Ability to pay (GDP)	-14	137	44	117	-88
Sovereignty (Population)	-37	30	30	81	-7
Egalitarian (Emission)	-5	-3	-9	-11	-3
Per Land area	-2	63	-75	109	24

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association, 5) Kyoto target for Sweden is +4% but in Marrakech, the target was changed to -4% at the request of the Swedish government, 6) 1990 carbon dioxide emission level measured in million ton.

Comparing the distribution of emission rights, according to a social welfare function, the one most similar to the Kyoto protocol distribution is the distribution derived from maximizing the Bernoulli-Nash welfare function, where society strives at equalizing the welfare differences between societies.

The distribution derived from the Utilitarian welfare function has a completely different allocation of emission rights as compared to the Kyoto protocol. The Eastern European countries and the Former Soviet Union will, in this case, carry a much higher burden and decrease their emissions by 39 percent, relative to 1990 emission level. Utilitarianism completely disregards the inequalities of society and therefore, the emission is reduced such that the sum of utility is maximized. Emission reduction is cheaper in the Eastern countries and therefore, a bulk of the reductions should be carried out there. If the income elasticity of marginal utility is one, and the welfare function is of Utilitarian form, the equity weight is such that it implies the permit price to be equalized across regions.

In view of the Swedish government's new approach to sharpen its target from +4% to -4%, or even reduce it further, these different equity views rather suggest the opposite direction for the target, i.e. an increase in emission from the 1990-level. One exception is the Egalitarian equity rule, where the initial distribution is based on the distribution of emissions in 1990. In this case, Sweden must decrease its emission by 11 percent, as compared to the 1990 emission level, due to its low emission level in the base year. For the remaining regions, the egalitarian rule corresponds quite well with the Kyoto rule.

Table 6 shows the welfare changes from the different distributions. As can be expected after looking at table 5, the Utilitarian view of society will give the Eastern countries high welfare costs corresponding to -4.5 percent as compared to the reference scenario.

The distribution of permit rights based on the more ad hoc rules, such as rules based on GDP and population, will give high positive welfare effects for all OECD regions, except OECD-America. In these scenarios, OECD-America, the Eastern European countries and the Former Soviet Union will carry most of the burden of the emission reduction.

Table 6. Welfare. Percentage change relative to the reference scenario 2010.

Distribution rule	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]
Kyoto distribution	-1.1	-0.8	-0.5	-0.6	-0.9
Utilitarian	-0.5	-0.2	-0.1	-0.1	-4.5
Bernoulli-Nash	-1.2	-0.6	-0.4	-0.4	-1.0
Ability to pay (GDP)	-1.4	0.2	0.7	0.6	-38.2
Sovereignty (Population)	-3.6	0.0	0.2	0.1	-0.4
Egalitarian (Emission)	-1.0	-0.8	-0.6	-1.1	-1.0
Land area	-0.7	-0.3	-19.0	4.4	1.5

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

Table 7. Permit price \$/tCO2.

Distribution rule	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]
Kyoto distribution	64.4	97.9	63.0	86.7	4.4
Utilitarian	32.7	32.7	32.7	32.7	32.7
Bernoulli-Nash	69.3	73.9	52.4	60.5	5.2
Ability to pay (GDP)	88.3	0.0	0.0	0.0	483.4
Sovereignty (Population)	204.6	6.6	0.0	0.0	4.5
Egalitarian (Emission)	60.0	96.9	65.9	137.1	5.5
Land area	54.6	0.0	1969.5	0.0	0.0

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

Permit price, i.e. the marginal cost of abatement, varies considerably between both scenarios and regions. Comparing only the distributions based on welfare and focusing on Sweden, the permit price varies between 60.5 \$/tCO2 when assuming a Bernoulli-Nash welfare function down to 32.7\$/tCO2 for the distribution based on the utilitarian welfare function. When the distribution is based on GDP or population, the Swedish permit price is even zero, which indicates that the distribution of permits allows for more permits than needed to follow the production in the reference scenario. The variation in permit price reflects the differences in distribution arising from the equity judgments in the social welfare function.

4.5 Introducing international carbon trade.

It is useful to consider the impact of an international agreement to reduce greenhouse gases as being carried out in two steps. First, by signing the international agreement, a large group of countries have accepted national-specific levels of abatement efforts. Ceilings on national emissions are set on basis of distributional considerations as discussed in section 4.4. Second, the agreement envisages a series of "flexible mechanisms" based on economic incentives and trade that might be used. These mechanisms are primarily viewed as a means to achieve the environmental objective at a lower cost, thereby improving economic efficiency.

In this section, I assume the different distributional rules from the previous section to hold and an international permit market for carbon to be set up, which will introduce efficient reductions of carbon dioxide throughout the Kyoto regions. The abatement of carbon dioxide will be preformed where it is cheapest and cost efficiency is achieved.

Table 8. Welfare. Percentage change relative to the reference scenario 2010.

Distribution rule	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]	Sum of welfare changes in all Annex 1 countries
Kyoto distribution	-0.8	-0.4	-0.3	-0.2	2.7	-0.43
Utilitarian	-0.5	-0.2	-0.1	-0.1	-4.5	-0.41
Bernoulli-Nash	-0.9	-0.3	-0.3	-0.1	2.3	-0.43
Rawls	-3.3	-1.5	-1.9	-1.2	51.8	-0.74
Ability to pay (GDP)	-1.0	1.0	0.5	1.1	-13.9	-0.38
Sovereignty (Population)	-1.5	-0.0	0.3	0.7	1.6	-0.42
Egalitarian (Emission)	-0.8	-0.4	-0.3	-0.3	2.4	-0.43
Land area	-0.7	0.3	-1.3	1.0	7.8	-0.46

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

In almost all scenarios, the introduction of international permit trade increases welfare in all regions, i.e. there are gains from trade. One of the exceptions is the "Ability to pay" scenario, where OECD-Europe will decrease its welfare when the international permit market is introduced[7]. The difference in reduction

[7] In these scenarios, all regions must participate in the international trade with carbon permits.

requirements and the effects of terms of trade account for this result. In the no-trade case, OECD-Europe faces a zero permit price which will induce comparative advantages for energy-intensive goods. When international trade is imposed, this advantage vanishes and is not offset by the positive effect of permit sales.

The other exception from the fact that international permit trade increases welfare is the case of the utilitarian welfare function. In this case, an identical solution to the non-trade case is observed, i.e. international trade with permits has no effect on the economies of the world, due to the fact that equity weights are equal to one. If the equity weights are one, the optimal rule of welfare maximization without trade is to distribute initial permit rights such that the permit price is equal in all countries. If trade with permits is introduced, no trade will take place, since the marginal cost of abatement is already equalized across the Kyoto region.

Table 9. Permit price \$/tCO2[8].

Distribution rule	Permit price \$/tCO2
Kyoto distribution	33.5
Utilitarian	32.7
Bernoulli-Nash	33.3
Rawls	38.5
Ability to pay (GDP)	32.0
Sovereignty (Population)	33.1
Egalitarian (Emission)	33.5
Land area	33.9

Manne and Richels (1995) note that "the rules for the allocation of emissions rights imply that there will be wealth transfers, but empirically we have found that the general equilibrium effects of these transfers are too small to influence the overall level of emissions". This is not the case in this study. The international permit price will differ, depending on the initial distribution of permits, which implies that the distribution of permits does not only have distributional effects between regions, but also real effects on the world economy, i.e. Coase's theorem[9]

[8] A recent survey by Springer (2003) presents the carbon dioxide permit price of 16 different models of different types (CGE, Integrated Assessment models, energy system models and Emission trading models) to be between 3 to 74 \$/ton CO_2. The results presented here are within this range.

[9] Coase's theorem states that provided: (i) property rights are well-defined and enforced; (ii) all parties have complete information; (iii) the costs of bargaining are negligible; and (iv) there are no

will not apply. In the extreme case, the Rawlsian rule, where all initial emission permits are distributed to the poorest region (The former Soviet Union and the Eastern European states), the permit price will be 38.5 \$/ton CO_2, which can be compared to the case when the equity rule is based on initial GDP, where the permit price is 32 \$/ton CO_2. This is a difference of more than 20 percent. Redistribution of income due to the Rawlsian distribution of permit rights will expand the Eastern region compared to the other regions within the agreement. The Eastern economies demand more fossil fuels in their production per output and therefore, the demand for permits will increase while the supply is constant. Hence, the price of permits will be higher as compared to the other cases where more permits are initially distributed to less carbon intensive regions. In other words, the effects of a reallocation of permit rights affect prices in other markets (not only the permit market) and move the economy from one Pareto-efficient allocation to another. Even if I disregard the extreme case of the Rawlsian distribution rule, the difference between the lowest and the highest permit price is six percent. This must also be considered as non-negligible.

Oliveira Martins and Sturm (1998) try to clarify the discussion initiated by Chichilnisky and Heal (1994) regarding the fact that in some cases, efficiency and equity may not be treated separately. They claim this question to only be relevant when the abatement externality is present in the utility function. They also show that if the question is to maximize a utility function subject to an emission constraint and with no abatement externality in the utility function, as in this section, equity and efficiency are separable. However, according to the results of this study, they have neglected the fact that in a general equilibrium setting, sufficiently large changes in the distribution of emission rights might give income effects and then, efficiency and equity may not be separable. Oliveira Martins and Sturm run the GREEN model (Burniaux et al. 1992) as an example of this problem and conclude: "It may happen, in some cases, that small differences appear between the model simulated scenarios having the same abatement target but different permit allocations. This can be caused either, by the approximate numerical solution provided by the resolution algorithm, or by the different dynamic adjustment paths between scenarios. It is not the non-separability between equity and efficiency with causes the gap". Their example consists of two different

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income effects, the bargaining between agents will ensure an outcome which is independent of the initial distribution of property rights, and moreover is Pareto efficient.

distributions; one based on historical emissions and the other on population. These two distribution rules were also studied in this paper, and gave similar permit prices, but my results show that it is possible to get income effects if the distribution rules are more extreme.

The real effects arising in the above analysis suggest that the cooperative solution of the greenhouse gas problem will differ depending on the choice of equity rule, not only as a consequence of new weights on damages and costs as in Tol (2001), but also due to the income effect.

5. The Cooperative Solution with Distributional Weights.

If damage costs are introduced into the utility function, it is possible to find a cooperative solution to the greenhouse gas problem. This has, for example, been studied in Fankhauser et al. (1996), Nordhaus (1994) and Tol (2001). The cooperative solution for other environmental problems, like the acid rain problem, has been more extensively studied in e.g. Mäler (1989, 1993), Kaitala et al. (1995) and a review is found in Mason (1996). Only a few studies have recognized that costs and benefits should be weighted to reach an equitable cooperative solution. Tol (2001) has included equity consideration in his cost-benefit analysis, but he only recognizes that the different equity weights alter the weights on damages and costs. The result from section 4 indicates that the distribution of weights will also give an income effect that changes the final optimal outcome. In this section, I will show how the different assumptions of equity, through the welfare function, will influence the result of the cooperative solution.

In search of the cooperative solution, a utility function must be defined, consisting of both income and damage. The costs of the project will, in this case, be estimated through the GTAP-EG model and will consist of the abatement cost of reducing CO_2 emission in the year 2010. The benefit side occurs in the form of greenhouse damage avoided. The damage on the environment will be connected to the stock of emission and not the flow. However, the flow until the year 2010 will affect the stock, and therefore the future damages. The discounted change in damages from the emissions in the year 2010 will constitute the benefits of the emission reduction project.

The greenhouse gases are stock pollutants, because only the atmospheric concentration (the stock) affects the climate. Stock pollutant problems are usually analyzed in a dynamic framework. However, a static framework has the advantage of being more accurate (non-linear) in its representation of climate and damage functions. Therefore, I closely follow the work by Fankhauser and Kverndokk (1996) and set up a static analysis of the cooperative solution of the greenhouse gas problem.

5.1 A static global warming game.

In this static game, I am only interested in the outcome of the year 2010 (period 0). Each player maximizes its income in the base period (2010), but is also considering the warming bequest caused by its action. This static game requires pre-specified or exogenous future emission paths,[10] and the only decision variable is the emission in period 0, i.e. the year 2010.

Without cooperation between the players in the game, each player i maximizes its own utility function, u_{i0}, with respect to its own emissions in period 0, E_{i0}. I assume the following utility function, which has a time and damage dimension as opposed to the utility in section 3

$$u_{i0} = C_{i0}(E_{i0}) + \sum_{t=1}^{\tau} C_{it}\delta_i^t - \sum_{t=0}^{\tau} D_{it}\left(\sum_j E_{jt}\right)\delta_i^t \tag{4}$$

where $\overline{E_{it}}$ are the exogenously determined CO_2-emissions for player i at time t, t=1,2,3..τ. The present value of future income $\sum_{t=1}^{\tau} C_{it}\delta_i^t$ is exogenous with a discount factor δ_i^t [11], and variable D_{it} is the damage cost for country i at time t, given the global emissions at time t.

The first-order conditions for the non-cooperative game lead to a Nash equilibrium, where the marginal cost of abatement is equal to the discounted sum of future marginal damages for country i

$$\frac{\partial C_{i0}}{\partial E_{i0}} = \sum_{t=0}^{\tau} \frac{\partial D_{it}}{\partial E_{i0}}\delta_i^t . \tag{5}$$

[10] Fankhauser and Kverndokk (1996) highlight the connection to the dynamic problem, p. 86.

[11] $\delta_i^t = \frac{1}{1+\Delta}$.

In the cooperative case, the social welfare function is maximized, i.e. $\max W = W(u_1, u_2, \ldots u_n)$. This social optimum will differ as compared to the study by Fankhauser and Kverndokk, since I add an equity dimension when introducing the welfare function and not simply adding the costs and damages[12].

The first-order condition for the cooperative game is that the equity-weighted marginal cost of abatement should equal the sum of the equity-weighted discounted sum of future marginal damages for all countries within the agreement

$$\frac{\partial W}{\partial u_i}\frac{\partial u_i}{\partial C_{i0}}\frac{\partial C_{i0}}{\partial E_{i0}} = \sum_{j=1}^{n}\sum_{t=0}^{\tau}\frac{\partial W}{\partial u_j}\frac{\partial u_j}{\partial D_{jt}}\frac{\partial D_{jt}}{\partial E_{i0}}\delta_j^t . \tag{6}$$

The damage function[13] is assumed to have the following form:

$$D_{it}(T_t) = k_i(1+h_i)^t\left(\frac{T_t}{\Lambda}\right)^{\gamma} . \tag{7}$$

Annual damage grows proportionally with income, where the rate of economic growth in country i is h_i. k_i denotes the damage for country i caused by a hypothetical temperature increase of $\Lambda ^\circ C$ in period 0. This means that the damage becomes $D_{i0}(T_0) = k_i$ for a temperature rise of $T_0 = \Lambda$. Finally, γ, determines the degree of convexity of the damage function.

The temperature constraint (T_t) describes the reaction of temperature to a change in atmospheric CO_2-concentration. The relation between concentration and the equilibrium change in the mean global temperature is assumed to have the following quasi-logarithmic form

$$T_t = \alpha \cdot w \ln\left(\frac{Q_t}{Q_p}\right) + (1-\alpha)T_{t-1} , \tag{8}$$

[12] This corresponds to a utilitarian welfare function.

[13] The damage function follows directly from Fankhauser and Kverndokk (1996); for a deeper description, the reader is advised to look at their paper.

where Q_t is the atmospheric greenhouse gas concentration at time t and Q_p the pre-industrial CO_2-concentration. The delay parameter, α, determines the speed of adjustment and w is a climate parameter for climate sensitivity of 2.5°.

The greenhouse gas stock constraint is represented by a carbon cycle, and CO_2 is assumed to dissipate at a constant rate σ, thus

$$Q_t = \lambda EM_{t-1} + (1-\sigma)Q_{t-1}, \tag{9}$$

where EM_{t-1} denotes total emissions in period $t-1$. Parameter λ translates emission units (GtC) into concentration units (ppm). Total emissions, EM_t, are determined in the emissions equation (10) and are the sum of all greenhouse gases emitted in period t

$$EM_t = \sum_g \beta_g S_{gt}, \tag{10}$$

where the emission levels, S_{gt}, are exogenously given in all periods and for all gases g, except the CO_2-emission from fossil fuels in period 0, $S_{F0} = \sum_i E_{i0}$. Variable β denotes the airborne fraction of gas g.

Tables 10 and 11 show values for all parameter in the damage function. Most parameters are from Fankhauser and Kverndokk (1996); however, some data are updated so that period 0 corresponds to the year 2010.

Table 10. Damage from a hypothetical 2.5 °C temperature rise (k-values, bn$)

Regions	Low case	Medium case	Upper case
OECD-America	104.9	139.9	209.9
OECD-Europe(excl. Sweden)	92.4[a]	123.2[a]	184.8[a]
Sweden	2.3[b]	3.1[b]	4.7[b]
OECD-Pacific	100.1[a]	133.6[a]	200.3[a]
Former Soviet Union and Eastern Europe	18.6	24.8	37.3
The rest of the world	135.8	181.1	271.7
Total world	454.2	605.7	908.6
(% GWP)	(1.5%)	(2%)	(3%)

a) Differ from Fankhauser and Kverndokk. Other OECD country is here divided into OECD-Europe, Sweden and OECD-Pacific, Fankhauser et al (1997) is used to divide the regions.
b) Subtracted from the OECD-Europe damage by the same share as the Swedish GDP of total OECD-Europe GDP.

Table 11. The climate parameters

Parameter	Value	Comments
α	0.10	Delay parameter for lag of 30 to 50 years
w	3.61	Climate parameter, for climate sensitivity of 2.5 °
Q_p	280	Pre-industrial CO_2-concentration in ppm
λ	0.47	Conversion factor GtC to ppm
σ	0.005	Dissipation rate, for atmospheric lifetime of 200 years
Δ	0.005	Discount rate
S_{OCO2t}	2.2053[a]	Other CO2-emissions in the base year 2010 (GtC)
	0.5%	Annual growth rate from base year emissions
S_{OGHGt}	5.0048 [a]	Other GHG-emissions in base year 2010 (GtC)
	0.5%	Annual growth rate from base year emissions
S_{Ft}	As soc. Opt	Emission from fossil fuels in base year 2010 (GtC)
	1.5%	Annual growth rate from base year emissions
β_{OCO2t}	0.5	Airborne fraction of other CO_2 gases
β_{OGHGt}	1.0	Airborne fraction of other greenhouse gases
β_{Ft}	0.5	Airborne fraction of CO_2 from fossil fuels
Λ	2.5	Temperature rise corresponding to the k values (2*CO_2)
γ	1, 2, 3	Degree of convexity in the damage function
h_i	2.6% for the ROW 1% for all other countries	Economic growth rate

a) Updated from 2000 to 2010 by the annual growth rates as in the above table.

Two different social welfare functions of utilitarian and Bernoulli-Nash type are maximized to find the social optimum. Table 12 gives the first-order conditions for the cooperative case, depending on the equity judgments prevailing in the different social welfare functions.

Table 12. First-order conditions in the cooperative game.

Social welfare function		First-order conditions
$W_0 = \sum_i u_{i0}$	Utilitarian	$\frac{\partial C_{i0}}{\partial E_{i0}} = \sum_{j=1}^{n} \sum_{t=0}^{\tau} \frac{\partial D_{jt}}{\partial E_{i0}} \delta_i^t$
$W_0 = \prod_i u_{i0}$	Bernoulli-Nash	$\frac{\partial C_{i0}}{\partial E_{i0}} = \sum_{j=1}^{n} \left[\frac{u_{i0}}{u_{j0}} \sum_{t=0}^{\tau} \frac{\partial D_{jt}}{\partial E_{i0}} \delta_i^t \right]$

The marginal cost of abatement for country *i* is equal to the equity-weighted discounted sum of future marginal damages for all countries within the agreement. If a utilitarian social welfare function is assumed, the equity weights are equal to one for all countries. When a Bernoulli-Nash welfare function is assumed, the equity weight for country *i* is equal to the relative utility between country *i* and country *j*. If utility is lower in country *j*, as compared to country *i*, the marginal damage for country *j* will be weighted by a parameter larger than one. In other words, poor countries' marginal damages will be given a higher weight as compared to rich countries in the Bernoulli-Nash case.

The level of emission reduction will to a large extent, depend on the shape of the damage function, but also on the assumed value judgment hidden in the social welfare function. The gamma value determines the convexity of the damage function and is a parameter with great uncertainty. Fankhauser and Kverndokk use gamma values varying from 1 to 3. This is also done in this study but I have chosen to present only simulation results corresponding to γ equals two. If gamma is smaller/larger than two the marginal damages become smaller/larger, which will induce a lower/higher reduction of CO_2 emission in the cooperative solution. Different k-values, i.e. damage cost estimates, also influences the cooperative solution (high k-values = large emission reductions, low k-values = low emission reductions). To keep the number of simulations presented down to a reasonable number, I have chosen to show values based on the medium and high case for the k-values in table 10.

5.2 The cooperative outcome for the Kyoto countries.

If the equity weights are incorporated in the cooperative analysis for the Kyoto countries, the total amount of carbon dioxide reduction depends on the welfare function assumed and to a great extent also on the shape of the damage function (see tables 13 and 14).

Table 13. Distribution of permits relative to the 1990 emission level.
The cooperative solution for the Kyoto countries.

Distribution rule	k-value	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]	Total Annex 1
Kyoto distribution		-7	-3	-8	-4	-2	-5
Utilitarian	Medium	12	18	6	6	-34	-2
Bernoulli-Nash	Medium	-1	8	0	2	-2	0
Utilitarian	High	8	17	3	5	-37	-6
Bernoulli-Nash	High	-8	4	-5	0	-3	-5

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

Table 14. Welfare. The cooperative solution for the Kyoto countries.
Percentage change relative to the reference scenario 2010.

Distribution rule	k-value	OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]
Kyoto distribution	Medium	-1.2	-0.7	-0.7	-0.8	-0.6
Kyoto distribution	High	-1.0	-0.4	-0.8	-0.7	-0.1
Utilitarian	Medium	-0.1	0.4	0.1	0.1	-3.0
Bernoulli-Nash	Medium	-0.7	-0.1	-0.2	-0.2	-0.3
Utilitarian	High	-0.0	0.8	-0.1	0.3	-4.1
Bernoulli-Nash	High	-1.0	0.1	-0.5	-0.3	0.0

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

If k is equal to the medium value, the equitable cooperative solution for the Annex 1 countries results in a more relaxed total Annex 1 CO_2 constraint as compared to the Kyoto target, regardless of which social welfare function is assumed. Comparing the results from section 4.4 with these results, the same tendencies in the distribution of emissions rights are observed. For example, if a utilitarian social welfare function is assumed, the Former Soviet Union and Eastern Europe will substantially reduce their emissions, while the other OECD counties will increase their emissions from the year 1990. If k is assumed to take the high estimated damage values, the total emission target for the Annex 1 countries is more in line with the Kyoto target and if a Bernoulli Nash welfare function is assumed the distribution of emission rights is fairly similar to that proposed by the Kyoto protocol.

As pointed out by Tol (2001) the differences in the total reduction target in the cooperative solution (comparing the same damage function) evolve from the differences in equity weights. The equity weights put different weights on the regions marginal damages so that the larger the distasted for inequality, the larger are the weights on poor countries marginal damages, which will correspond to a more rigid cooperative solution (less carbon dioxide emission). However, this phenomenon is counteracted by the income effect pointed out in the previous sections. The income effect indicates that the higher is the distaste for inequality the higher is the negative effect on real income, which would induce a less stringent CO_2 reduction target. Contrary to Tol (2001) the results in this study indicate that the higher distaste for inequality the less stringent is the optimal CO_2 reduction target for the cooperative countries. This may be due to the income effect but also to the differences in marginal cost functions and different model approaches. An integrated assessment model (as in Tol (2001)) has several feedback effects from the environment to the economy while the economy is more endogenous and better described in a general equilibrium model (as in this study). In the relatively "short" perspective (up to 2010), the feedback effects from the environment to the economy of increased CO_2 emissions will be less important while the economic reaction to the CO_2 constraint is more pronounced.

5.3 The cooperative outcome for the world.

The cooperative outcome for the world means much higher emission reductions, since the marginal damages of all regions are taken into consideration. The region "Rest of the World" has a high level of marginal damage cost, which will affect the outcome. However, this region will not abate as much as the other regions. One reason for this is that they have low utility per population, which will affect the equity weights and lead to a low marginal cost. This marginal cost will not, as in the case of the Former Soviet Union and the Eastern states, result in a large cutback in emission since the reduction possibilities are not so extensive.

Table 15. Distribution of permits relative to the 1990 emission level.
The cooperative solution for all regions.

Distribution rule	OECD America[1]	OECD Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]	Rest of the world	Total Annex1 countries	Total World
Kyoto	-7	-3	-8	-4	-2	-	-5	-
Utilitarian M[5]	-18	1	-9	2	-65	5	-27	-16
Bernoulli-Nash M[5]	-42	-20	-25	-11	1	8	-24	-13
Utilitarian H[6]	-28	-6	-18	-1	-73	-9	-36	-27
Bernoulli-Nash H[6]	-53	-28	-35	-18	-8	-6	-33	-24

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association. 5)M=Medium k-value, 6) H=High k-value

The Annex 1 countries will carry a high burden as opposed to the region the Rest of the World in all scenarios. Welfare is affected by two opposite effects. First, a high emission reduction rate for most countries will have a negative effect on consumption and thereby welfare, and second the decrease in damages has a positive effect on welfare. That is, even though the emission reduction is quite substantial in the scenarios with high *k*-values, the welfare effects are not as high as would be expected, since I measure welfare changes both in changes in costs and in damages.

Table 16. Welfare. The cooperative solution for all regions.
Percentage change relative to the reference scenario 2010.

Distribution rule		OECD-America[1]	OECD-Pacific[2]	OECD-Europe[3]	Sweden	Former Soviet Union and Eastern Europe[4]	Rest of the world
Utilitarian	Medium	-0.1	2.9	1.5	1.9	-17.3	-1.8
Bernoulli-Nash	Medium	-4.7	-0.5	-1.4	-0.8	1.5	-3.2
Utilitarian	High	-0.1	5.0	0.4	2.9	-23.4	-1.5
Bernoulli-Nash	High	-7.3	-0.5	-4.3	-1.5	3.1	-4.2

1) USA and Canada, 2) Australia, New Zeeland and Japan, 3) EU and EFTA members not including Sweden, 4) Former Soviet Union and the Central European Association.

6. Summary and Conclusion

Allocating the burden between parties is at the focus of interest in the international negotiation process on climate protection. The principles for allocation are many, and in this study, I focus on principles based on economic welfare theory. This approach makes the allocation equitable and consistent with economic theory. I also include analyses of some more ad hoc rules such as "ability to pay", sovereignty", "Egalitarian principles" and distribution per land area. My main conclusion from these simulation exercises is that the distribution rule based on the different assumptions on the social welfare function and some other more ad hoc distribution rules creates quite large changes in welfare, distributions of emission rights, real income and the total emission target.

At first, the simulations are restricted to the case where the Kyoto protocol's total emission target for the Annex 1 countries is assumed to hold. Scenarios built on the utilitarian welfare function and the more ad hoc distribution rule "ability to pay" require large amounts of abatements for the Eastern European states and the Former Soviet Union. Another observation from these simulations is that among the distribution rules tested, that based on maximizing the Bernoulli-Nash social welfare function is closest to the burden sharing agreement within the Kyoto protocol. The Bernoulli-Nash social welfare function strives at reducing the welfare differences between regions.

If the focus is turned to Sweden, I observe that the discussions at the political level to reduce emissions even further than the -4% target are not in line with any of the distribution rules tried in this study, except the case where emissions targets are based on the relative emissions of the base year.

The second step involves the introduction of international carbon permit trade. The main conclusion from these simulations is that the permit trade is not unaffected by the initial distribution of carbon permits. The distribution of permits does not only have distributional effects between countries but also real effects on the world economy. This result contradicts earlier literature in the field (e.g. Oliveira Martins and Strum 1998), where the income effect is neglected. The cost of reducing carbon dioxide may vary up to twenty percent, depending on the choice of the initial allocation of permit rights.

The third step includes the introduction of a damage function and a cooperative solution is found, i.e. the social optimal total emission reduction and the distribution of permits. Also in these scenarios, different social welfare functions are assumed to include equity and value judgments in the optimal solution. . Contrary to Tol (2001) the results indicate that a higher distaste for inequality results in less stringent CO_2 reduction targets for the cooperative countries. The equity weights put different weights on the region's marginal damages, so that the larger the distaste for inequality, the larger are the weights on poor countries' marginal damages, which leads to a more stringent target for CO_2 the larger is the distaste for inequity. This effect is also included in Tol's analysis. However, the income effect pointed out in section 4 counteracts these phenomena. It indicates that the higher is the distaste for inequality, the higher is the negative effect on real income, which would subsequently lead to a less stringent CO_2 reduction target. Naturally, there are difficulties in comparing the two types of model results emerging from Tol's analysis with an integrated assessment model and the results from the general equilibrium model used in this study.

The numbers presented in this paper should be treated with great caution, as they depend on the model parameterization. The climate change impact estimates are particularly uncertain, and drive the numerical results to a substantial extent. The qualitative results are those that should be in focus, i.e. that the underlying equity judgment in the social welfare function will influence the distribution of initial permit rights, welfare distribution and the total emission target.

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Household Transport Demand in a CGE-Framework[*]

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Abstract

The aim of this study is to show how households' demand for transport services can be improved in a Computable General Equilibrium model. The new extended model is then used for numerical simulations to test how the Swedish economy reacts to a carbon target. The results indicate that the extended consumption module gives new insight into the problem of greenhouse gas reduction. A differentiation between trip purposes and trip length, a complementary relationship between work journeys and labor supply, and a subdivision of households by density of population and income influence the numerical results in a direction increasing the negative welfare effect of a carbon target as compared to the non-extended model. Naturally, the new extended model will also give additional information about changes in the household transport mode choice, induced by a change in the carbon target.

IV

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1. Introduction

A large and growing carbon dioxide (CO_2) emission source for Swedish households is the demand for private transport, i.e. car use. More than 60 percent of households' emissions originate from gasoline (i.e. car use), and if their use of public transports is added, households' demand for transport services accounts for an even larger source of emission. In a survey by Dahl and Sterner (1991), it is concluded that: "estimates of gasoline demand elasticity have important policy implications, since there is fairly strong evidence that the average long-run income elasticity is greater than one, if unchecked, we can expect gasoline demand to continue to grow"[1]. In a growing economy with intentions to reduce emissions of greenhouse gases, policy intervention to reduce gasoline demand is therefore necessary. These policy interventions need to be evaluated before set into action and it is important that there exist good tools to help policy makers evaluate the intended environmental policy.

Computable General Equilibrium (CGE) models are increasingly used for the quantitative assessment of greenhouse gas policies. The general equilibrium framework offers a distinct advantage over partial equilibrium models, since it allows instruments for tackling the externalities to be evaluated within the framework of overall tax policy. It takes into account the large number of interactions between these instruments, public finance and the rest of the economy, which has induced a growing demand for models more accurately describing the behavior of each agent regarding her energy use. In most studies, the main focus has been on either model improvement regarding energy production or stationary energy demand within the industry (i.e. Böhringer 1998). In this paper, however, I focus on transport issues and, in particular, how households' demand for transport services can be improved in CGE-models. Johnsson (2003) has improved his Swedish CGE-model regarding transport, but he only considers transport demand by industry. A few other modelers have also improved their CGE models regarding household demand for transport services (Van Dender 2001; Mayeres 2000 and Munk 2003); however, they mainly focus on congestion and accordingly, extensions of importance for that question. They also use stylized data. In this paper, I take a broader approach and start off by examining the variables of

[1] There are two reasons for the increasing demand for gasoline, either an increased demand for larger and more gasoline dependent cars or an increased demand for longer or more frequent trips.

importance for household behavior reported in the literature of transport economics. Then, I use real data and incorporate as many variables as possible in the improved model. A number of various simulation experiments are then performed to see whether the model will provide any new information relevant to policy makers. The main conclusion from the numerical simulations is that, on a macro level, households are less responsive to price changes in the extended model as compared to the "generic" EMEC model[2].

The structure of this paper is as follows. The next section briefly reviews econometric studies presenting the variables determining the travel behavior of households. Section 3 presents the thoughts behind the new consumption module, while section 4 describes the numerical model (extended with the new consumption module). Section 5 shows the simulation results and section 6 presents the sensitivity analysis. The final section concludes and summarizes.

2. Household travel behavior.

There exist a large number of papers on household choice of transport mode in the economic transport literature. Most of these are based on econometric analysis (e.g. Dieleman et al. 2002; Hanson 1982; de Palma et al. 2000 and Watson 1974), but quite a large number of partial numerical models are also used to analyze the questions of transport choice and related questions (e.g. Parry and Bento 1999). In computable general equilibrium models, transport services are usually modeled as any other commodity, and are sometimes not even treated as a separate good, even though the analysis focuses on the effects of a climate policy. Naturally, there are some studies that have developed the transport side of the household consumption function in a CGE model framework. Mayeres (1999) has several transportation modes and a distinction of peak and off-peak transport in her model. Munk (2003) discusses several important features to be included in a CGE-model, but his model only includes some of these, such as road capacity, and he acknowledges private road transport to be a complement to non-market use of time, i.e. leisure. However, both Mayers and Munk mainly focus on congestions and their models may still be further developed to catch the important features emerging from the econometric studies.

[2] The "generic" EMEC model refers to the original version of the EMEC model, not considering the new features of the consumption module raised in this paper.

Several variables have been shown to be of importance for the household's choice of transport mode; car ownership having been pointed out as the most crucial (e.g. Dieleman et al. 2002 and Vibe 1993). "If people have a car, they use it" (Vibe 1993). The car ownership decision, however, has been found to primarily be related to the household income level (e.g. Palma et al. 2000 and Nolan 2003). Golob (1989) studies the influence of income and car ownership on trip generation by mode. He concludes that: All effects of income on car travel can be explained by income-to car ownership linkages. Car ownership also directly affects trips by public transport and bicycle, but for each of these two modes, there are additional effects of income that are not explained by car ownership. In particular, public transport demand is a superior economic commodity (an increasing function of income, controlling for car ownership), and bicycle demand is an inferior commodity (a decreasing function on income).

Another variable, not so commonly recognized in the transport literature, is that trip purpose is of importance for household behavior. Watson (1974) showed trip purpose to be of great importance for the choice of transport mode. For work trips and business trips, the time-cost hypothesis is important, but for recreational trips, the choice also depends on other variables. The reason may be that the recreational trip is part of the recreation; in other words, the trip itself generates "extra" utility when consumed in this way. In his numerical analysis, Van Dender (2001) explores the fact that the choice of transport mode differs between purposes and he adds that work journeys are related to labor supply. He concludes that the welfare effects of a transport-tax reform depend largely upon the impact on the labor supply. The infrastructure is not equally distributed in a country like Sweden, which makes the transport choice hinge on place of residence. The most extensive and frequently cited study on the impact of population density on travel demand is that by Newman and Kenworthy (1989). In 1999, they undertook a follow-up of their previous study where they analyzed the costs of car dependency in 37 cities across the world. Both studies show a decrease in gasoline use in increasing population density. A negative relationship between urban density and energy use for transport was also found for relatively smaller cities in Denmark, Norway and Sweden (Naess 1995). Johansson-Stenman (2002) estimates the individual driving distance by car and public transport use in Sweden. One of his conclusions is that people living in large cities are less likely to drive than people living in the countryside. Hence, the frequent statement that people in the countryside would, on average, suffer more from fuel-price increases seems correct. However, he has also seen that this effect is not as large as is often claimed, and that, in fact, drivers' mean driving- distance is about the same in city areas as in the countryside.

Strømsheim Wold (1998) discusses the importance of travel distance for the transport mode choice. She finds it important to differentiate between short and long journeys in her numerical model since she experienced an unrealistic increase of air travel in the model result when increasing the tax on carbon dioxide emission. For example, the transport mode choices for a trip to the grocery store do not include airplane, while a longer holiday journey includes transport choices between all types of modes, including airplane.

Sociodemographic variables (individual and household attributes) are found to influence the choice of transport mode and transport frequency. Hanson (1982) found sociodemographic variables (sex, education, income, age and household size) to outweigh spatial ones in explaining overall trip frequency and travel for particular purposes, but spatial factors cannot be overlooked in explaining patterns of trip distribution. However, Dieleman et al. (2002) contrast Hanson's results and show both spatial and sociodemographic variables to be of importance when explaining travel behavior. In their study, the sociodemographic variable of great importance is the presence of children in the household, especially in combination with two partners with paid work. The combination of work and family leads people to experience time pressure, which evidently leads to a more frequent use of the private car. Nolan (2003) shows gender and age to also influence the transport mode choice. While car ownership and use are more likely for households headed by a male, even in households owning a car, bus and taxi fare expenditures are higher for households headed by a single female. The effects of the age of the head of the household on car use, bus fare expenditure and taxi fare expenditure correspond to the expectation of younger households being more mobile and engaged in more activities than older households.

Since the seminal papers by Becker (1965) and Gronau (1977), economists have devoted serious attention to the determinants of the value of time. Also in the transport literature, the value of time has been frequently discussed (for a recent survey, see Jara-Diaz, 2000), especially in the transport literature on congestion. When discussing congestion, time and furthermore, the value of time, is essential since travel time is the objective variable in these studies. However, the value of time will also influence household behavior in other areas of transport economics.

For example, an environmental tax introduced to change the agent's travel behavior, will affect the price of the transport service. However, the agent does not only consider the price of the different transport modes, but also the difference in travel time.

3. Properties of the consumption function for transports

Ideally, all variables mentioned above (car ownership, income, trip purpose, population density, sociodemographic variables, distance traveled and value of time) should be implemented in a consumption module in a CGE model. The availability of data restricts the intention of making a "complete" consumption module for a CGE model. After a thorough search for data, I found the following databases that may be used for the new consumption module: the national accounts, environmental accounts, income distribution data, travel survey, expenditure survey, education at the municipal level and energy statistics at the municipal level.

Combining these databases and the variables of importance for the transport mode choice has led me to divide the households into nine different household groups. First, they are subdivided into three groups depending on disposable income[3]. The first two income groups are represented by the two lowest levels of quartile disposable income; the third income group is represented by a merger of the two highest quartile disposable income groups. Second, each income group is subdivided into three groups, depending on the density of population where the households have their residence. The first group has its residence in one of the major cities in Sweden[4], the second group consists of households from middle-size towns[5] and the third group consists of households from sparsely populated areas[6]. These nine groups will capture some of the features of the variables shown to be of importance for the household-transport mode choice. The income groups will

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[3] Quartile 1 (0-150 000), Quartile 2 (150 000-240 000), Quartile 3 and 4 (240 000-∞).

[4] H-region 1, 8, and 9: Stockholm, Gothenburg and Malmö

[5] H-region 3: Municipalities with more than 90 000 inhabitants within a 30 km radius form the municipal center. And H-region 4: Municipalities with more than 27 000 and less than 90 000 inhabitants within a 30 km radius from the municipal center and more than 300 000 inhabitants within a 100 km radius from the same point.

[6] H-region 5: Municipalities with more than 27 000 and less than 90 000 inhabitants within a 30 km radius from the municipal center and less than 300 000 inhabitants within a 100 km radius from the same point and H-region 6: Municipalities with less than 27 000 inhabitants within a 30 km radius from the municipal center.

capture some of the differences in behavior, due to different income levels, while the division based on residence will capture some of the differences in infrastructure.

It has not been possible to distinguish car ownership at the macro level. However, car ownership has been shown to primarily depend on income, for example in Golob (1989). Therefore, the division of households into income levels is an indirect way of incorporating car ownership. Other sociodemographic variables like the number of children in a household, could not be incorporated, due to insufficient data. The databases in question did not have enough observations to allow for one more division of households.

In an attempt to incorporate the different behaviors due to differences in trip purpose and distance traveled, I have added three new goods into the consumption module; work journey and long (more than 100 km) and short (less than 100 km) leisure journey. Each type of transport service is then produced by using different transport modes: car, bus, train and rail. For work trips, an additional slow mode (bicycling and walking) is added, which is only priced according to the time spent bicycling or walking. Air travel is an additional transport mode only possible for long leisure journeys.

In the new consumption module, work trips will be treated differently as compared to leisure trips. Its strong relationship to labor supply has led me to model work trips as a perfect complement to labor supply, i.e. for each unit of labor supply, a constant amount of travel is expected. Naturally, this constant level may be accomplished by different transport modes. An additional feature for work trips which is commonly used in analyses on congestion (e.g. Parry and Bento 1999 and Van Dender 2001), is that the price of work trips does not only include the price of transport mode, taxes and subsidies, but also the value of the time taken by each transport mode

To illustrate the connection between work journeys and labor supply, I will introduce a small reduced analytical model. The model will only include one household and three goods to illustrate the implications of the connection between labor supply and work journeys.

$$u = U(x_0, N) + T(x_1), \tag{1}$$

where u is household utility. $U(x_0, N)$ is the utility of consumption of the composite consumption commodity, x_0, and leisure N. $T(x_1)$ is the utility of work trips, x_1, which, for simplicity, is assumed to be equal to x_1. Labor supply, L, and commuting trips are assumed to be complements, such that

$$\beta \cdot L = x_1. \tag{2}$$

Consumers face a budget constraint such that

$$P_L \cdot L = \sum_{i=0}^{1} P_i (1 + t_i) x_i, \tag{3}$$

where P_L is the price of labor net of tax, P_1 the price of work journeys excluding taxes, t_1, and P_0 is the numeraire and untaxed. The consumer also faces a time resource constraint. Time may be spent on leisure, labor supply and work journeys.

$$\bar{L} = L + N + \alpha x_1 , \tag{4}$$

where α is the time spent on each work trip unit. Insert equation 3, 4 and 2 into 1 and the first-order condition of the utility maximization problem is

$$u_L = U_{x_0} \cdot (P_L - P_1(1 + t_1)\beta) - U_N(1 + \alpha\beta) + \beta = 0, \tag{5}$$

where u_L is the first derivative of u with respect to L and U_{x_0} and U_N is the first derivative of U with respect to x_0 and N.

When rearranging the first-order condition, the marginal rate of substitution between leisure and consumption $\frac{U_N}{U_{x_0}}$ is shown not only to depend on the price of labor[7] but also on the price and tax of commuting, the share of work trips and the time factor for work trips

[7] If the connection between labor supply and work trips is not acknowledged, the marginal rate of substitution between leisure and consumption simply equals the wage rate, P_L.

$$\frac{U_N}{U_{x_0}} = \frac{P_L - P_1(1+t_1)\beta + \frac{\beta}{U_{x_0}}}{(1+\beta\alpha)}. \tag{6}$$

To further investigate the first-order condition, I total differentiate equation 5 to find the implications for changes in labor supply.

$$dL = \frac{-(U_{x_0,x_0}AL + U_{x_0} - U_{N,x_0}BL)(dP_L - P_1\beta dt_1)}{U_{x_0,x_0}A^2 + U_{N,N}B^2 - U_{x_0,N}AB - U_{N,x_0}AB}, \tag{7}$$

where $A = P_L - P_1(1+t_1)\beta > 0 \quad and \quad B = (1+\alpha\beta) > 0$. The second-order condition for the maximization problem tells us that the denominator of equation (7) is negative; that is, there is a positive effect on labor supply of a change in the price of labor, but a negative effect of a change in the tax on commuting trips, i.e. a tax on work journeys is, in fact, a tax on labor supply. This will be shown to be of importance when interpreting the numerical results in section 5.

If $dP_L > P_1\beta dt_1$, then dL is positive. If the relationship is reversed, the change in labor supply is negative due to changes in the price of labor. In other words, Equation 7 shows that we may get a backward-bending labor-supply curve if both wages and the tax on work trips change, i.e. labor supply may decrease despite a wage increase.

The next section will describe the CGE-model, where these consumption features have been incorporated.

4. The EMEC model

The basic framework of the EMEC model[8] was developed at the National Institute of Economic Research in Sweden. The model is a static computable general equilibrium model (CGE-model) for Sweden, for the analysis of the interaction between the economy and the environment. Through the work done in this study, the model is extended and referred to as the extended EMEC-model. In short, the extensions of the model focus on the private consumption function, which is completely new in this version of the model. However, some changes on the production side have also been necessary to accompany the new consumption module, mainly consisting of a disaggregation of the transport sector into five new sectors, but also a new foreign trade module. An algebraic model formulation and description of the data used, along with the exogenous parameter values, are presented in Appendix 1 and 2.

The basic framework of the extended EMEC model is well in line with mainstream CGE-models in the literature. However, it differs in some respect by including an energy input structure that is relatively more disaggregated and therefore facilitates simulations where substitution possibilities among energy inputs are possible. In the model, five energy commodities are specified: electricity, coal, oil, gas, and bio-fuels. There are three atmospheric emissions (CO_2, SO_2, NO_x) linked to the use of energy, which emerge from mobile and stationary sources but also from industry processes. What is noteworthy is that the links between sectors and emissions have been established via the use of energy in these sectors; the different emission contents of each type of fuel are identified using fuel-specific coefficients. Therefore, fuel substitution possibilities as a measure to minimize emissions are relatively realistically described.

Another advantage of the model is the well described energy and environmental tax system. Due to the disaggregation of energy commodities, energy and environmental taxes are well described. These taxes are not treated as ad valorem taxes as in most other Swedish CGE models (Bergman 1996; Harrison and Kriström 1999 and Hill 2001), but follow the structure of the tax system. In other words, the environmental tax is a tax on emissions[9].

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[8] A model description in Östblom 1999.

[9] The emission taxes are indexed by the GDP deflator.

However, the main difference between mainstream environmental CGE-models and the extended EMEC model is the consumption function, aiming at modeling the household substitution possibilities as realistically as possible in order to capture the true effects of an environmental tax, as discussed in section 3.

The extended model is built around several databases. The main set of data originates from the National Accounts for 1998, which is the calibration year of the model. The environmental accounts for the same year together with the National Accounts constitute the environmental module of the model. These datasets, together with the datasets used to construct the new consumption function (see section 3), result in an integrated economic-energy-transport dataset allowing for a disaggregation level of 21 industry sectors, 24 producer goods, 4 production factors, 3 emission types, 24 private goods and 9 household groups.

4.1 Model structure

The model is structured as follows. Goods are produced using primary factors and intermediate inputs. Primary factors include three types of labor: unskilled labor, technicians and non-technicians, and capital. Labor and capital are intersectorally mobile. The total domestic time constraint (leisure time, labor supply and time spent on work journeys) and total capital stock are fixed at benchmark levels. The output is sold in perfectly competitive markets, where producers and consumers maximize profits and utility, respectively. The model is closed with an exogenous ratio for the foreign trade balance of the economy. Imports are modeled according to the Armington assumption, while exports are assumed to be sold at an exogenously given world-market price with infinite demand and produced according to a constant elasticity of transformation function. The real exchange rate is chosen as a numeraire.

Production

The production of commodities is captured by aggregate production functions technology exhibiting constant returns to scale, and is characterized by substitution possibilities between various inputs. Nested constant elasticity of substitution functions with five levels is employed to specify the capital-labor-energy–material substitution possibilities (see Appendix 2, figure A1). The model allows sufficient levels of nesting to permit substitution between primary energy types, as well as between a primary energy composite and secondary energy, i.e. electricity. At the top level, a CES function describes the substitution possibilities between the energy-material aggregate and the value added aggregate. The value added branch, in turn, has three CES nests where the substitution possibility between capital and aggregate labor is shown at the top. The two subsequent levels show the substitution possibilities between unskilled and skilled labor, and non-technicians and technicians, respectively.

The other main branch, energy-material, shows the substitution possibilities between the two aggregates, energy and material. The material inputs are employed in fixed proportions, while the energy branch is, in turn, a CES function in three levels. At the top level in the energy branch, the substitution possibility between fuels and electricity is shown. At the next level, fuels constitute a mix of solid fuels and non-solid fuels, while biofuel and coal, and oil and gas, are substituted through two CES functions to constitute the aggregate solid and non-solid fuels, respectively.

Consumption

Households are subdivided into nine different groups, according to income and density of the population in the area where the household has its residence. Consumer group preferences are modeled as nested CES functions according to figure A2 in Appendix 2. At the top level of the consumption tree, utility is separable into work trips and total consumption (excluding work trips). Work trips is a perfect complement to labor supply, and the consumer chooses different transport modes according to a CES function to fulfill the aggregate amount of work trips needed for each labor supply unit. The price of work trips does not only include transport mode, taxes and substitutes, but also the value of the time spent on each transport mode.

At the second level of the consumption tree, the consumer decides how to allocate his income between consumption of goods/services and leisure. He has the possibility of consuming his labor endowment as leisure or supplying it at the clearing labor market (together with time spend on work trips), i.e. unemployment is modeled as "voluntary".

The composite good, consumption of goods and services, in turn, consists of three main branches, one for goods related to housing (i.e. rents and energy), the second related to leisure trips and the third branch consists of remaining goods and services not including rents, energy and transport services. The consumer chooses his housing composite commodity by choosing between rents and heating. Heating, in turn, is a composite commodity of fuel, district heating and electricity, while fuel is a mix of the different fuels in the model, i.e. oil, gas, coal, bio-fuels. The choice of leisure trips is a choice between the composite goods long leisure trip and short leisure trip. Finally, the transport modes constituting the composite long and short leisure trips are chosen according to a CES function. The last branch constitutes a constant elasticity of substitution consumption function of the remaining goods and services.

The household income available for consumption consists of payments received from the sale of primary factors, plus government transfers, minus private investment and payments on foreign debt. Each household group has a different amount of labor income according to the benchmark data. The remaining variables in the budget constraint are divided among the consumers according to their share of total expenditure, in the absence of better data. Income from foreign debt to each household group is calculated as the residual, so that total expenditure is equal to income minus savings (investments).

Taxes

Households and producing sectors of the economy are subject to energy and environmental taxes. Exemptions in the energy and environmental taxation of manufacturing and agricultural industries are taken into consideration in the model framework. Private consumption is also subject to VAT and other indirect taxes, while the use of labor is subject to social security fees and income tax.

Data

It is not possible to present the whole data set for the model, due to the huge amount of data needed to support the EMEC model. Table 1 shows some of the most important features of the benchmark data for the simulation results in this paper.

Table 1. Benchmark data

Household groups[1]	Labor income share of disposable income	CO_2 tax paid as a share of disposable income	Car (petrol) work trip expenses as a share of total expenditure	Total petrol expenses as a share of total expenditure
Big 1	0.2	0.065	0.003	0.031
Big 2	0.5	0.068	0.010	0.041
Big 3	0.9	0.074	0.018	0.050
Middle 1	0.2	0.039	0.004	0.023
Middle 2	0.8	0.063	0.012	0.041
Middle 3	0.8	0.064	0.017	0.043
Sparsely1	0.3	0.028	0.002	0.021
Sparsely 2	0.8	0.032	0.008	0.025
Sparsely 3	0.7	0.046	0.013	0.034

1) The Household groups are described in Appendix 1 table A2

5. Numerical results

In this section, the numerical simulation results from the extended EMEC model are presented and compared to different versions of the model to illustrate the new information that will be given by the extended model.

All numerical results are presented in relation to the benchmark case, which in these simulations is the reference year 1998. The variable that will represent the social cost of emission reduction is the change in equivalent variation that can be interpreted as the amount the consumers are willing to pay for the policy to be implemented. To be able to present a macro variable representing the total welfare cost of implementing a carbon target, the welfare of each household is assumed to be additive with equal weight, i.e. a utilitarian social welfare function is assumed.

In all scenarios, the CO_2 target is fulfilled by gradually increasing the CO_2 tax for all agents and fossil fuels, unless differently stated in the text. The policy is assumed to be tax neutral and I consider two possibilities for the government to return the increased tax revenue to the households. The first is referred to as lump-sum replacement. In this case, government transfers to the household increase by the same amount as the change in government revenue. In the second type of replacement scheme, the social contribution fee is reduced for firms while the government revenue is held constant.

5.1 The effect of a carbon target

One significant finding is that all scenarios involving a revenue neutral carbon tax increase will decrease aggregate welfare. This is a common result for similar models, see Hill (2001), and Harrison and Kriström (1999). The model result seems to indicate a much lower gain from using the tax recycling replacement scheme (see table 2) than for example Hill (2001). Some of the difference may be explained by differences in nesting structure in two models, but the main difference evolves from the connection between work journeys and labor supply and also the fact that work journeys spend time resources. If the extensions are not modeled, the labor supply will increase more in the tax recycling scenario as compared to the extended model result and thereby increase growth in the economy and reduce the welfare effects of the increased CO_2 tax.

Table 2. Total cost of CO_2 emission reduction (percentage change in aggregate equivalent variation)

CO_2 reduction Percent from benchmark scenario	Lump-sum replacement	Tax recycling	Lump-sum replacement Work trips not additionally taxed	Tax recycling Work trips not additionally taxed
-5 %	-0.31	-0.29	-0.28	-0.25
-10 %	-0.66	-0.62	-0.61	-0.55
-15 %	-1.08	-1.01	-1.00	-0.90
-20 %	-1.56	-1.46	-1.45	-1.31
-25 %	-2.12	-1.99	-1.98	-1.79
-30 %	-2.77	-2.60	-2.60	-2.34
-35 %	-3.54	-3.30	-3.33	-3.00
-40 %	-4.43	-4.12	-4.18	-3.77
-45 %	-5.43	-5.06	-5.17	-4.69
-50 %	-6.56	-6.16	-6.34	-5.82

In this model, there are other forces counteracting this effect. Despite an increase in net wages, the labor supply increase is very small in the tax recycling scenario. One of these counteractive forces is an increase in net wage, that is, an increase in the value of time, influences the choice of work trip transport mode. An increase in the value of time makes car travel relatively cheaper, which will increase the emissions of CO_2 and thereby the carbon tax in order to fulfill the carbon target. Another effect is that the tax recycling scenario benefits households with a high disposable income, see table 4 (since they have a higher share of labor income in their budget constraint). These households also have the highest demand for fossil fuels, which will increase the carbon tax, as compared to the lump-sum replacement scenario. All in all, labor supply increases slightly as compared to the benchmark, but is lower as compared to a generic model and higher as compared to the lump-sum replacement scenario, see table 3.

Table 3. Percentage change in total labor supply as compared to the benchmark scenario due to a 10% CO_2 reduction.

	Lump-sum replacement	Tax recycling	Lump-sum replacement Work trips not additionally taxed	Tax recycling Work trips not additionally taxed
Labor supply	-0.08	0.01	-0.04	0.09

The complementary structure on work trips and labor supply indicates a tax on work journeys to simply be a tax on labor (see page 8 equation 7). A tax exemption on work trips is therefore one way of reducing the negative welfare effect of the increased CO_2 tax. As a hypothetical experiment, I assume that work trips can be exempt from additional CO_2 tax above the benchmark level. Table 2 shows that the welfare effect may be reduced, both in the lump-sump replacement scenario and the tax recycling scenario, if work trips are not subject to additional taxes.

In fact, the implications that tax on work trips is indirectly a tax on labor supply which will decrease welfare are recognized by the Swedish authorities and a type of tax exemption for work journeys is currently applied in the Swedish system. It is possible to make tax reductions by the end of year in the income-tax return form. However, if this policy is simulated, it turns out to be approximately the same as the lump-sum scenario. This type of replacement scheme will only give an income effect, but no substitution effect. The distorting tax on work trips and thus indirectly on labor supply is still in place when the household chooses its transport mode. A policy implication from these results would therefore be that from an aggregate welfare perspective it is better to reduce labor tax in a tax recycling policy scheme, instead of letting households deduct their work-trip expenses in their income-tax return form.

Different household groups

The division of households into several groups may be used for studying distributional effects between groups. A significant finding is that the more sparsely populated is the area where the household lives, the larger are households' costs of implementing the CO_2 target. This is not surprising, since there are less public transports but a more frequent use of private cars in the countryside.

Another tendency is for low income groups to be more affected than high income groups when the tax recycling replacement is simulated since disposable income in the different groups constitutes different amounts of labor income. When tax recycling is used, groups with relatively high labor income are favored since they have a high labor income share in their disposable income. If lump-sum replacement is simulated, a tendency towards the opposite becomes visible.

Table 4. Percentage change in EV from the benchmark scenario due to a 10% CO_2 reduction.

Household groups[1]	Lump-sum replacement	Tax recycling	Lump-sum replacement Work trips not additionally taxed	Tax recycling Work trips not additionally taxed
Big 1	-0.46	-0.98	-0.55	-1.32
Big 2	-0.42	-0.56	-0.45	-0.66
Big 3	-0.45	-0.21	-0.43	-0.08
Middle 1	-0.65	-1.09	-0.71	-1.36
Middle 2	-0.80	-0.71	-0.75	-0.61
Middle 3	-0.82	-0.69	-0.69	-0.50
Sparsely 1	-1.02	-1.41	-1.08	-1.65
Sparsely 2	-0.81	-0.66	-0.77	-0.55
Sparsely 3	-0.96	-0.89	-0.79	-0.69

1) The household groups are described in Appendix 1 table A2

Subdividing the population into 9 household groups will affect the results of the model as compared to a version of the model where there is no difference between households (see table 5). This is due to the differences in consumption behavior and sources of income for household groups. Responses on the transport modes are higher in the one-household model. There is more substitution from private transports towards public transports in the one-household model. All differences in effects are due to households' behavior regarding the choice of transport mode. The aggregated model also neglects the fact that the income effect of the lump-sum replacement of the new tax revenue differs between household groups as does their transport behavior. However, the differences between the one-household model and the extended EMEC model are very small at a macro level.

Table 5. Percentage change in household consumption of commodities as compared to the benchmark scenario due to a 10% CO_2 reduction.

	Lump-sum replacement	Lump-sum replacement One Household
Road and sea transports used for work trips	0.8	0.9
Road and sea transports used for short leisure trips	-1.6	-0.9
Road and sea transports used for long leisure trips	1.5	1.6
Railways used for work trips	0.8	1.0
Railways used for short leisure trips	-0.1	0.4
Railways used for long leisure trips	2.8	3.1
Airlines used for long leisure trips	3.3	3.4
Slow mode used for work trips	1.1	1.0
Gasoline used for work trips	-3.3	-4.2
Gasoline used for short leisure trips	-11.0	-11.2
Gasoline used for long leisure trips	-9.8	-10.2

Value of time

So far, I have chosen to value time at the net wage for all time use (leisure, work trips and labor supply), but when studying work trips, this is not totally in line with the empirical results. The value of time is often assumed to be around 80 percent of net labor income in transport models (i.e. Persson et al. 2003 and Small 1992). I have chosen to assume a value of time corresponding to the net income to avoid additional effects from valuing time differently, depending on its use. If I were to assume a lower value of time only for work trips, a carbon tax increase will have a negative effect on labor supply, since more time is now spent on work trips (as compared to a case where the value of time is 100 percent of the net wage). The lower value of time will decrease welfare more than in the case of a higher value of time, since the effects of a lower labor supply outweigh the positive effects of changing from car use to bus, rail or walking (see table 6).

Table 6. Percentage change in total EV, labor supply and household consumption of different transport modes as compared to the benchmark scenario due to a 10% CO_2 reduction and lump-sum replacement

	Value of time during work trips = net wage	Value of time during work trips = 0.8·net wage	Value of time during work trips = 0.1·net wage
EV total	-0.66	-0.67	-0.73
Labor supply	-0.08	-0.09	-0.13
Petrol work	-3.61	-3.95	-5.92
Road work	0.79	0.87	1.27
Rail work	0.72	0.79	1.33
Slow work	1.14	1.28	2.34

Comparing the Extended EMEC model to the Generic EMEC model.

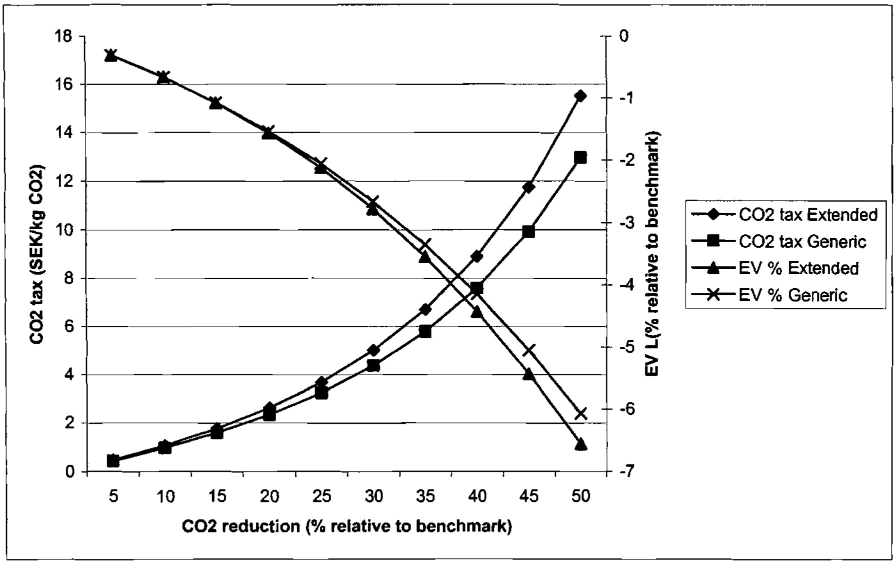
Treating all households as one, the transport modes as any other commodity and not taking into consideration the time spent on work trips, takes us back to the generic EMEC model. Table 7 shows that petrol use, and all transport modes, decrease less in the Extended EMEC model. The connection between labor and work trips, trip purpose and, to some extent, the division of households will make the substitution between transports and other commodities less elastic. In the Generic EMEC model, the transport modes are substituted like any other commodity and not modeled in a separate CES branch, which is why it is possible to decrease the overall transport demand in the generic EMEC model to such a large extent.

Table 7. Percentage change in household consumption of different transport modes as compared to the benchmark scenario due to a 10% CO_2 reduction.

	Lump-sum replacement Extended EMEC model	Lump-sum replacement Generic EMEC model framework
Petrol	-8.2	-12.1
Road	0.3	-1.5
Rail	1.2	-0.2
Air	3.2	-0.1

The tax rate in the extended EMEC model is higher for the same CO_2 target, as compared to the Generic EMEC model framework, which also generates a larger welfare cost. This is mainly due to the complementary relationship between labor supply and work trips, which will hold back the substitution away from transports into other goods. However, also the nesting structure into long and short leisure trips, in the extended model, will decrease the substitutability between transport modes and other goods. Figure 1 shows the marginal cost on the left axes, while the right axes show the welfare cost for the Swedish economy.

Figure 1. The marginal cost curves and the welfare change of the Swedish Economy for the two model versions.



6. Sensitivity analysis

There is always uncertainty about the elasticity values in a CGE model, and I will therefore employ an unconditional, systematic sensitivity analysis for the elasticities in the new consumption function[10]. I follow the procedure suggested by Harrison and Vinod 1992 and thereby investigate how robust the simulation results are to plausible perturbations of those elasticities. Thus, I assume a uniform distribution for each elasticity value in the consumption function and run independent simulations. The model is repeatedly solved for the 10 percent CO_2 target scenario, with elasticity values perturbed from the value used in the study. The procedure is run until the sample size is 2000.

Table 8. Result of the unconditional sensitivity analysis. 10 percent CO_2 target scenario with lump sum-replacement.

	Point estimate	Mean	Standard deviation	Maximum value	Minimum value
EV	-0.66	-0.66	0.04	-0.56	-0.76

[10] This paper concerns the extension of the consumption module and I would like to test the robustness of the results emerging from this feature. Therefore, the production elasticities are not subject to the sensitivity analysis.

The results in Table 8 show the aggregate result to be rather robust. The point estimate and the mean value of the unconditional sensitivity analysis are almost the same, and the standard deviation is only 0.04. A 90-percent confidence interval for the Equivalent Variation parameter is $-0.72 \leq EV \leq -0.60$. The sensitivity analysis shows more fluctuations in the results at the micro level. For example, the standard deviation is 0.23 for long holiday trips.

The elasticity of labor supply is one of the most important elasticities in the extension of the model. As discussed earlier, a tax on work trips is indirectly a tax on labor, due to the complementary relationship between the two variables. Therefore, I have made a conditional sensitivity analysis regarding labor-supply elasticity as a complement to the above unconditional one, i.e. labor-supply elasticity is changed conditional on unchanged values of all other elasticities.

Table 9. Result of the conditional sensitivity analysis. 10 percent CO_2 target scenario with lump-sum replacement.

	Substitution elasticity consumption/leisure 1.1 Labor supply elasticity 0.1	Substitution elasticity consumption/leisure 0.9 Labor supply elasticity -0.1	Substitution elasticity consumption/leisure 1.5 Labor supply elasticity 0.3
EV	-0.66	-0.66	-0.68
Labor supply	-0.08	-0.07	-0.11

The results in table 9 indicate that there is no substantial effect on aggregate welfare of changes in the consumption/leisure substitution elasticity. The increase in labor supply elasticity will increase the response of the carbon tax. An increase in tax will lead to a substitution towards leisure, and less labor supply. If the elasticity of substitution is increased, more leisure is consumed, which hence decreases labor supply as shown in table 9. Less labor supply means less work journeys and a lower tax, which contradicts the first effect but not to the extent that the total direction of the increased tax is changed.

7. Summary and conclusions

The purpose of this project is to show how household demand for transport services can be improved in CGE-models used for greenhouse gas policy analysis. The new features of the consumption module are applied to a static general equilibrium model called EMEC. The results of the extended model indicate that by taking most of the variables shown to be of importance in the econometric transport literature into consideration, the effect of a carbon target will give somewhat different results, as compared to the non-extended model. A differentiation between trip purposes and trip length, a complementary relationship between work journeys and labor supply, and a subdivision of households by density of population and income, influences the numerical results in a direction increasing the negative welfare effect of a carbon target, as compared to the non-extended model.

The complementary relationship assumed to exist between work trips and labor supply counteracts the decrease in transport demand due to an increasing CO_2 tax. This is why the CO_2 tax rate is higher in the extended as compared to the non-extended model and subsequently, the welfare effects become higher in the extended model. At the micro level, the transport mode choices also differ between the extended and the non-extended model. In the extended model, a substitution away from private transports (car use) to public transports (road, train and air) takes place, whereas a general substitution away from both public and private transports is visible in the non-extended model. This micro result is due to the division into trip purpose and the general nesting structure, so that transport demand cannot be directly substituted for any other commodity.

Due to lack of data, it is not possible to make all the extensions that should be included in the ideal model. In my opinion, the sociodemographic variables, e.g. the number of children in the household, are the most important aspects not taken into consideration here. Households with children have been shown to be very inelastic to changes in the relative price of petrol, and thereby react quite differently as compared to households without children. Another variable that has been pointed out as the most crucial for household transport demand choice is car ownership. However, as pointed out in section 2, car ownership has been shown to primarily depend on income. Therefore, the extended EMEC model in some sense incorporates the influence of car ownership on transport behavior, by subdividing the household into income groups. In this version of the model, income elasticity is one, since CES utility functions are assumed. This may be seen as a drawback since the household does not change its behavior (price elasticities) if income moves up or down, i.e. if a household is subdivided into a specific group, it remains in that income group during the simulations. However, the change in income/welfare is relatively small when examining a carbon target, so the effect of this negligence is probably small.

My main conclusions are that it is important to incorporate all new features of the extended EMEC model so that it more realistically models the economy's reactions to a carbon target. The model is now more relevant for policy simulations, since it will give results indicating how the demand for different transport modes changes, what are the distributional effects between different income groups and how labor supply is influenced by an increase in the carbon dioxide tax rate. The sensitivity analysis shows the model to be rather robust to perturbations of the new consumption elasticities. However, these elasticities must be subject to further research.

Appendix 1: The Extended EMEC model – Sectors, goods and exogenous parameter.

Index and parameters

Index

i	Production sectors
PR	Industry goods
H	Household groups
FN	Household goods
NE	Non-energy goods (households)
TRS	Transport mode for short trips
TRL	Transport mode for long trips
TRW	Transport mode for work trips
FNO	Household goods not including transport services, energy or rents
PO	Pollution

Parameters

σ_{SL}	Elasticity of substitution between technicians and non-technicians
σ_{L}	Elasticity of substitution between skilled and unskilled labor
σ_{VA}	Elasticity of substitution between capital and labor aggregate
σ_{Y}	Elasticity of substitution between value added and material and energy aggregate
σ_{EM}	Elasticity of substitution between energy aggregate and material aggregate
σ_{E}	Elasticity of substitution between energy goods
σ_{F}	Elasticity of substitution between fuels
σ_{LF}	Elasticity of substitution between liquid fuels
σ_{SF}	Elasticity of substitution between solid fuels
$b_{i,pr}$	Parameter in the transformation matrix between industry output and producer goods
$a_{pr,fn}$	Parameter in the transformation matrix between producer goods and consumer goods
$\delta_{pr,*}$	Calibrated parameters in the CES production functions
β_h	Share of work transport needed for each unit of labor supply
ae_{pr}	Calibrated parameter in the export demand function
σ_{WT}	Elasticity of substitution between different transport modes for work trips
σ_{C}	Elasticity of substitution between consumption of goods and services and leisure
σ_{NT}	Elasticity of substitution between short and long leisure trips

σ_{NTS} Elasticity of substitution between different transport modes for short leisure trips

σ_{NTL} Elasticity of substitution between different transport modes for long leisure trips

σ_{PKL} Elasticity of substitution between the aggregate goods house, other goods and leisure trips

σ_{O} Elasticity of substitution between different goods and services not including transport and housing

σ_{HO} Elasticity of substitution between the aggregate goods heat and rents

σ_{HE} Elasticity of substitution between the aggregate goods fuels, district heating and electricity

σ_{F} Elasticity of substitution between different fuels used for heating

Table A1 Industries and good category in these extended EMEC model

Production sector	Goods
1. Agriculture	1. Agriculture
2. Fishery	2. Fishery
3. Forestry	3. Forestry
4. Mining	4. Bio-fuels
5. Other industries	5. Mining
6. Pulp and paper mills	6. Coal
7. Chemical industries	7. Other industries
8. Basic metal industries	8. Pulp and paper
9. Engineering	9. Chemicals
10. Petroleum refineries	10. Basic metal
11. Electricity supply	11. Manufacturing
12. Gas distribution	12. Petroleum refined products
13. Water and sewage	13. Raw oil
14. Construction	14. Electricity
15. Road	15. Gas
16. Rail	16. Water and sewage
17. Air	17. Construction
18. Post and telecommunication and transport support	18. Road
19. Services	19. Rail
20. Real estate	20. Air
21. Public services	21. Post and telecommunication and transport support
	22. Services
	23. Real estate
	24. Public services

Table A2 Household groups

Household group	Income group	Region
Big 1	0-150 000	H-region 1, 8, and 9: Stockholm, Gothenburg and Malmö
Big 2	150 000-240 000	
Big 3	240 000-∞	
Middle 1	0-150 000	H-region 3: Municipalities with more than 90 000 inhabitants within a 30 km radius from the municipal center and H-region 4: Municipalities with more than 27 000 and less than 90 000 inhabitants within a 30 km radius from the municipal center and more than 300 000 inhabitants within a 100 km radius from the same point.
Middle 2	150 000-240 000	
Middle 3	240 000-∞	
Sparsely 1	0-150 000	H-region 5: Municipalities with more than 27 000 and less than 90 000 inhabitants within a 30 km radius from the municipal center and less than 300 000 inhabitants within a 100 km radius from the same point and H-region 6: Municipalities with less than 27 000 inhabitants within a 30 km radius from the municipal center.
Sparsely 2	150 000-240 000	
Sparsely 3	240 000-∞	

Table A3. Commodities in private consumption

Commodity	Label in National Accounts
1. Food, beverage and tobacco	Food, beverages and tobacco
2. Clothing and footwear	Clothing and footwear
3. Furniture etc	Furniture, carpets and repairs
	Household textiles and other furnishings
4. Household goods	Major household appliances
	Glassware, tableware and household utensils
	Household services
5. Gross rents	Gross rents and water charges
6. Recreation	Photographic equipment
	Other recreational goods
	Entertainment and photo services
	Gambling, lotteries etc.
	Books, newspapers and magazines
	Expenditure in restaurants, cafés and hotels
7. Private transport	Personal transport equipment
	Repair charges, parts and accessories
	Compulsory tests of cars
8. Road and sea transports used for work trips	Bus, local traffic and ships, Cabs, Removal
9. Road and sea transports used for short leisure trips	
10. Road and sea transports used for long leisure trips	
11. Railways used for work trips	Railways
12. Railways used for short leisure trips	
13. Railways used for long leisure trips	Railways
14. Airlines used for long leisure trips	Airlines
	Services of travel agencies and air charter
15. Services	Household services excl. domestic services
	Domestic services
	Other expenditures on cars
	Communication
	Radio and television
	Repairs to recreational goods etc
	Television licenses
	Veterinary services
	Services of barber and beauty shops etc
	Financial services
	Services n.e.c.
	Purchases abroad and foreigners' purchases
16. Goods n.e.c.	Medical care and health expenses
	Other recreational goods
	Goods for personal care
	Goods n.e.c.
17. Electricity	Electricity
18. Gas	Gas
19. Fuels	Liquid fuels, Other fuels
20. Gasoline used for work trips	Gasoline
21. Gasoline used for short leisure trips	Gasoline
22. Gasoline used for long leisure trips	Gasoline
23. Bio-fuels	Other fuels
24. Purchased heat	Purchased heat

Calibration and Parameter Values

Most CGE-models are calibrated for a specific year using an elaborated database. Prices of the calibration year are chosen as the base for price indices. This version of the EMEC-model is calibrated for the year 1998.

The calibration procedure runs along standard lines. I assume static equilibrium with perfect competition and solve for unknown constants of the utility function and the production functions. The model solution of the calibration year reproduces observed prices and quantities. Substitution elasticities in the CES-aggregators must be assembled for all nesting levels in production and consumption. This is primarily done by searching the literature for econometrically estimated values, preferably sector-specific values. For some of the values, reliable econometric estimate are scarce, and the values used are therefore subject to margin of error. Table A4 shows the substitution elasticities in the production functions for all sectors in the economy.

Table A4. Substitution elasticities in production sectors

Production sector	σ_{SL}	σ_L	σ_{VA}	σ_Y	σ_{EM}	σ_E	σ_F	σ_{LF}	σ_{SF}
1. Agriculture	1.7	1.1	0.5	0.3	0.5	0.6	0.7	0.8	0.9
2. Fishery	1.7	1.1	0.5	0.2	0.3	0.4	0	0	0
3. Forestry	1.7	1.1	0.5	0.3	0.4	0.5	0	0	0
4. Mining	1.7	1.1	0.8	0.3	0.4	0.5	0.6	0	0
5. Other industries	1.7	1.1	0.8	0.3	0.4	0.5	0.6	0.7	0.8
6. Pulp and paper mills	1.7	1.1	0.8	0.7	0.9	1.1	1.2	1.3	1.4
7. Chemical industries	1.7	1.1	0.8	0.7	0.9	1.1	1.2	1.3	1.4
8. Basic metal industries	1.7	1.1	0.8	0.7	0.9	1.1	1.2	1.3	1.4
9. Engineering	1.7	1.1	0.8	0.7	0.9	1.1	1.2	1.3	1.4
10. Petroleum refineries	1.7	1.1	0.3	0.2	0.3	0.5	1.1	1.5	1.8
11. Electricity supply	1.7	1.1	0.3	0.2	0.3	0.4	0	0	0
12. Gas distribution	1.7	1.1	0.3	0.2	0.3	0.4	0	0	0
13. Water and sewage	1.7	1.1	0.2	0.1	0.2	0.3	0	0	0
14. Construction	1.7	1.1	0.3	0.2	0.3	0.7	0	0	0
15. Road	1.7	1.1	0.8	0.6	0.7	0.8	0	0	0
16. Rail	1.7	1.1	0.8	0.6	0.7	0.8	0	0	0
17. Sea	1.7	1.1	0.8	0.6	0.7	0.8	0	0	0
18. Air	1.7	1.1	0.8	0.6	0.7	0.8	0	0	0
19. Post and telecommunication and transport support	1.7	1.1	0.8	0.6	0.7	0.8	0	0	0
20. Services	1.7	1.1	0.8	0.7	0.9	1.1	1.2	1.3	0
21. Real estate	1.7	1.1	0.6	0.5	0.8	1.2	0	1.5	0
22. Public services	1.7	1.1	0.7	0.1	0.7	1.1	1.2	1.3	0

There seems to be some consensus in the empirical literature for labor-capital substitution elasticities between 0.5 and 1.0 (see e.g. Caddy 1976 and Bovenberg et al. 1996). The distinction between different kinds of labor, used in EMEC, is not very common in CGE-modeling. Moreover, the elasticity might depend on the definitions of labor categories. The only basis for the numbers given in the table is a series of simulations where the shares of skilled labor and technicians were altered over a 10-year period. When elasticities are low, the relative wages are compressed too fast.

The price elasticities of exports and imports are chosen to be fairly high to emphasize that Sweden is a small country. The import elasticity is 4 and the constant elasticity of transformation in the export function is -4.

In table A5, the substitution elasticities for the new consumption function are presented. Some of these elasticities were found in similar consumption modules in the literature (Van Dender 2001). The sensitivity analysis presented in section 6 tests the robustness of the results based on these elasticities.

Table A5 Substitution elasticities in the consumption function

σ_{WT}	0.6
σ_{C}	1.1
σ_{NT}	1.1
σ_{NTS}	0.9
σ_{NTL}	0.8
σ_{PKL}	0.5
σ_{O}	0.9
σ_{HO}	0.3
σ_{HE}	0.6
σ_{F}	0.5

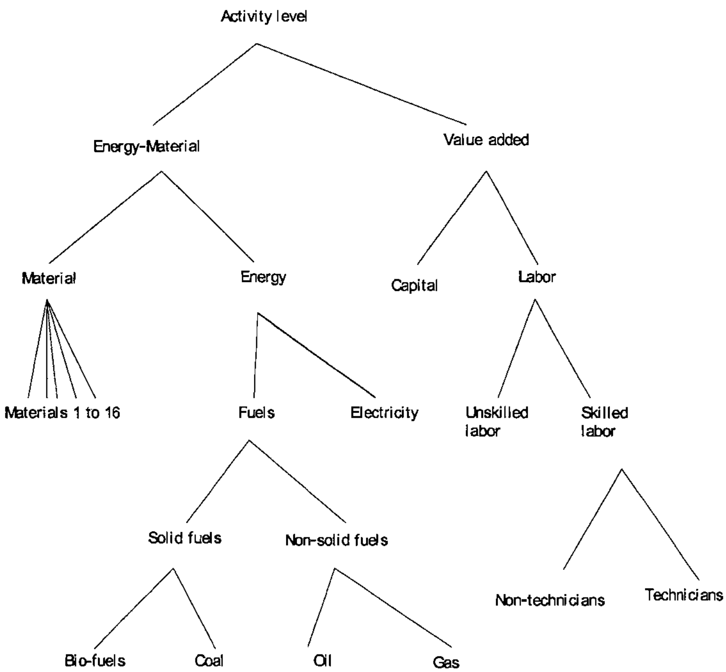
Appendix 2. The Extended EMEC model – An Algebraic model description

The Extended EMEC model (Environmental Medium Term Economic model) is formulated as a nonlinear system of inequalities using GAMS (Brooke 1992), and is solved using MINOS5 (Murtagh et. al. 2003). The inequalities are derived from the Arrow-Debreu general equilibrium conditions: Zero profit for producers (constant-returns to scale production), income balance for each consumer group and the government, and market clearance for all goods and factors and balanced trade with the rest of the world.

Producers

The domestic producers including public services use primary factor and intermediate goods to produce their output with a constant elasticity of substitution (CES), technology. Figure A1 describes the nested production tree.

Figure A1



All sectors and public services produce output Y_i according to

$$Y_i = \left(\delta_{i,EM} EM_i^{(\sigma_Y - 1)/\sigma_Y} + \delta_{i,VA} VA_i^{(\sigma_Y - 1)/\sigma_Y}\right)^{\sigma_Y / (\sigma_Y - 1)}, \quad \text{(A1)}$$

where EM_i is the aggregate of energy and materials and VA_i is a nested CES aggregate of capital, C_i and labor, L_i

$$VA_i = \left(\delta_{i,C} C_i^{(\sigma_{VA} - 1)/\sigma_{VA}} + \delta_{i,L} L_i^{(\sigma_{VA} - 1)/\sigma_{VA}}\right)^{\sigma_{VA} / (\sigma_{VA} - 1)}. \quad \text{(A2)}$$

Labor, in turn, is produced according to the next level in the CES production tree and constitutes a mix of unskilled, USL_i, and skilled, USL_i , labor

$$L_i = \left(\delta_{i,USL} USL_i^{(\sigma_L - 1)/\sigma_L} + \delta_{i,SL} SL_i^{(\sigma_L - 1)/\sigma_L}\right)^{\sigma_L/(\sigma_L - 1)}. \quad \text{(A3)}$$

At the bottom level of the value-added branch, skilled labor is produced with the help of technicians, TEC_i, and non-technicians, $NTEC_i$

$$SL_i = \left(\delta_{i,TEC} TEC_i^{(\sigma_{SL} - 1)/\sigma_{SL}} + \delta_{i,NTEC} NTEC_i^{(\sigma_{SL} - 1)/\sigma_{SL}}\right)^{\sigma_{SL}/(\sigma_{SL} - 1)}. \quad \text{(A4)}$$

The other main branch of the CES production tree is the energy material aggregate

$$EM_i = \left(\delta_{i,M} M_i^{(\sigma_{EM} - 1)/\sigma_{EM}} + \delta_{i,E} E_i^{(\sigma_{EM} - 1)/\sigma_{EM}}\right)^{\sigma_{EM}/(\sigma_{EM} - 1)} , \quad \text{(A5)}$$

where M_i is a Leontief aggregate of all goods and services used as inputs, not including energy goods, IM_i, and E_i is a CES aggregate of Electricity EL_i and Fuels, F_i

$$M_i = \min\left[IM_1, \ldots\ldots, IM_{NE}\right] \quad \text{(A6)}$$

$$E_i = \left(\delta_{i,F} F_i^{(\sigma_E - 1)/\sigma_E} + \delta_{i,EL} EL_i^{(\sigma_E - 1)/\sigma_E}\right)^{\sigma_E/(\sigma_E - 1)}. \quad \text{(A7)}$$

Fuel is subdivided into solid, SF_i and liquid fuels, LF_i

$$SF_i = \left(\delta_{i,BIO} BIO_i^{(\sigma_{SF} - 1)/\sigma_{SF}} + \delta_{i,COAL} COAL_i^{(\sigma_{SF} - 1)/\sigma_{SF}}\right)^{\sigma_{SF}/(\sigma_{SF} - 1)} \quad \text{(A8)}$$

$$LF_i = \left(\delta_{i,OIL} OIL_i^{(\sigma_{LF} - 1)/\sigma_{LF}} + \delta_{i,GAS} GAS_i^{(\sigma_{LF} - 1)/\sigma_{LF}}\right)^{\sigma_{LF}/(\sigma_{LF} - 1)}, \quad \text{(A9)}$$

where BIO is bio-fuels, and the rest of the energy goods are self explanatory.

The model distinguishes between industry output and producer goods. The industry output is transformed into producer goods using a fixed coefficient technology, that is,

$$Q_{pr} = \min\left[\frac{Y_{1,pr}}{b_{1,pr}},......,\frac{Y_{i,pr}}{b_{i,pr}}\right]. \tag{A10}$$

The goods and services demanded by private households, HC_{fn}, are transformed into consumer goods according to a fixed technology

$$HC_{fn} = \min\left[\frac{Q_{1,fn}}{a_{1,fn}},.....,\frac{Q_{pr,fn}}{a_{pr,fn}}\right]. \tag{A11}$$

Foreign and domestic consumers are assumed to differentiate between goods produced in Sweden and in other countries, i.e. the Armington-assumption applies. This means that domestic production for the domestic market are treated as qualitatively different from products imported from abroad. Domestic demand, DZ_{pr}, is an aggregation of domestic, OH_{pr}, and imported, IMP_{pr}, goods described by a CES function:

$$DZ_{pr} = \left(\delta_{pr,QH} QH_{pr}^{(\sigma_{DZ}-1)/\sigma_{DZ}} + \delta_{pr,IMP} IMP_{pr}^{(\sigma_{DZ}-1)/\sigma_{DZ}}\right)^{\sigma_{DZ}/(\sigma_{DZ}-1)}. \tag{A12}$$

Export demand, EXP_{pr}, is modeled as a choice of the producer to either produce for the domestic market or the export market at a fixed world price, $PEXP_{pr}$. The Swedish supply of goods and services is then:

$$Q_{pr} = \left(se_{pr,QH} QH_{pr}^{(\sigma_{se}-1)/\sigma_{se}} + se_{pr,EXP} EXP_{pr}^{(\sigma_{se}-1)/\sigma_{se}}\right)^{\sigma_{se}/(\sigma_{se}-1)}. \tag{A13}$$

The current account, B, is balanced, and is a constant share of GDP. This is the closing rule of the model

$$B = (EXPL - IMPL)/GDPL, \tag{A14}$$

where $EXPL$ and $IMPL$ are total exports and imports, respectively.

Consumers

Nine representative consumer groups, h, are assumed to choose among different goods and services by maximizing their utility. The utility functions are a four-level constant elasticity of substitution functions, with a separable part modeling work trips (see figure A2). At the top level, the consumer allocates his total resources between consumption of goods, services and leisure, $Cons_h$, (not including work trips) and work trips, WT_h

$$U_h = Cons_h + WT_h . \tag{A15}$$

The household then chooses different possible transport modes for work trips (TRW) according to a CES function

$$WT_h = \left[\sum_{TRW} \delta_{h,TRW} \left(HC_{h,TRW} \right)^{(\sigma_{WT}-1)/\sigma_{WT}} \right]^{\sigma_{WT}/(\sigma_{WT}-1)} . \tag{A16}$$

The sum of work trips and labor supply ($LTOT_h$) are perfect complements; in other words, aggregate work trips are a constant share of total labor supply for each household group

$$\sum_{TRW} HC_{h,TRW} = \beta_h LTOT_h , \tag{A17}$$

where β_h is the share of work transports needed for each unit of labor supply.

Total consumption of goods, services and leisure (not including work trips), is formed through the following CES functional form consisting of leisure, N_h, and consumption of goods and services (not including work trips), PKL_h

$$Cons_h = \left[\delta_{h,PKL} PKL_h^{(\sigma_C-1)/\sigma_C} + \delta_{h,NA} NA_h^{(\sigma_C-1)/\sigma_C} \right]^{\sigma_C/(\sigma_C-1)} . \tag{A18}$$

Total consumption of goods and services (not including work trips) is an CES aggregate of housing-related goods, HO_h (fuels for heating, electricity and rents), leisure trips and other goods and services, not including transports, energy or rents, O_h,

$$PKL_h = \left[\delta_{h,O} O_h^{(\sigma_{PKL}-1)/\sigma_{PKL}} + \delta_{h,HO} HO_h^{(\sigma_{PKL}-1)/\sigma_{PKL}}\right]^{\sigma_{PKL}/(\sigma_{PKL}-1)}. \qquad \text{(A19)}$$

The demand for other goods and services not including transports, energy or rents is described by a one-level CES demand function

$$O_h = \left[\sum_{FNO} \delta_{H,FNO} \left(HC_{H,FNO}\right)^{(\sigma_O-1)/\sigma_O}\right]^{\sigma_O/(\sigma_O-1)}, \qquad \text{(A20)}$$

where $HC_{h,FNO}$ constitute the demand for each good and services. The leisure trips may, in turn, then be formed through long, NTL_h, and short, NTS_h, trips

$$NT_h = \left[\delta_{h,NTL} NTL_h^{(\sigma_{NT}-1)/\sigma_{NT}} + \delta_{h,NTS} NTS_h^{(\sigma_{NT}-1)/\sigma_{NT}}\right]^{\sigma_{NT}/(\sigma_{NT}-1)} \qquad \text{(A21)}$$

At the next nest, the household has the opportunity of choosing between different transport modes for long, *TRL*, and short leisure trips, *TRS*, according to two CES functions

$$NTL_h = \left[\sum_{TRL} \delta_{h,TRL} \left(HC_{h,TRL}\right)^{(\sigma_{NTL}-1)/\sigma_{NTL}}\right]^{\sigma_{NTL}/(\sigma_{NTL}-1)} \qquad \text{(A22)}$$

$$NTS_h = \left[\sum_{TRS} \delta_{h,TRS} \left(HC_{h,TRS}\right)^{(\sigma_{NTS}-1)/\sigma_{NTS}}\right]^{\sigma_{NTS}/(\sigma_{NTS}-1)}. \qquad \text{(A23)}$$

The expenditures related to housing are rents ($HC_{h,rents}$) and energy related to heating and household electricity, HE_h

$$HO_h = \left[\delta_{h,RE} \left(HC_{h,RENTS}\right)^{(\sigma_{HO}-1)/\sigma_{HO}} + \delta_{h,HE} HE_h^{(\sigma_{HO}-1)/\sigma_{HO}}\right]^{\sigma_{HO}/(\sigma_{HO}-1)}. \qquad \text{(A24)}$$

Energy used for housing is subdivided into three main categories, district heating, $HC_{h,DHEAT}$, fuels used for heating, F_h, and electricity, $HC_{h,EL}$

$$HE_h = \left[\delta_{h,DH} \left(HC_{h,DHEAT}\right)^{(\sigma_{HE}-1)/\sigma_{HE}} + \delta_{h,F} F_h^{(\sigma_{HE}-1)/\sigma_{HE}} + \delta_{h,EL} \left(HC_{h,EL}\right)^{(\sigma_{HE}-1)/\sigma_{HE}}\right]^{\sigma_{HE}/(\sigma_{HE}-1)}$$
$$\text{(A25)}$$

At the last nest on the energy branch, fuels are subdivided into the different types of fuels possible in the model, $HC_{h,FUEL}$: oil, gas, bio, and coal. Fuels are then determined through a CES function

$$F_h = \left[\sum_{FUEL} \delta_{h,FUEL} \left(HC_{h,FUEL} \right)^{(\sigma_F - 1)/\sigma_F} \right]^{\sigma_F/(\sigma_F - 1)} . \tag{A26}$$

Consumers maximize U taking market prices as given, subject to a budget constraint

$$\sum_{FN} PHC_{FN} \cdot HC_{h,FN} \le PL_h \cdot LTOT_h + PC_h \cdot C_h + T_h + B_h - I_h , \tag{A27}$$

i.e., the value of consumption is less than or equal to the net income from primary factors (labor, $PL_h \cdot LTOT_h$, and capital, $PC_h \cdot C_h$), lump-sum government transfers , T_h and the exogenously given foreign exchange balance, B_h, minus investment, I_h. Income and expenditure of capital, investments, and foreign exchange balance are distributed between the nine household groups according a fixed share, depending on the initial expenditure. Naturally, this last assumption is very rough; however, this is my best estimate due to lack of data.

Supply of investment, I_h, is given by the exogenously given demand of investments, *INVS*, distributed in fixed proportions to each household type,

$$I_h = exshr_h \cdot INVS , \tag{A28}$$

and transfers to the household, T_h, is a given share of total government transfers.

$$T_h = exshr_h \cdot transfers . \tag{A29}$$

Labor supply, $LTOT_h$, equals labor endowment net leisure consumption and time spent on work trips. In other words, the total time endowment is:

$$\overline{LTOT}_h = N_h + LTOT_h + \sum_{TRW} \alpha_{h,TRW} HC_{h,TRW} . \tag{A30}$$

Each household supplies a fixed ratio of unskilled labor ($LUNSK_h$), technicians ($LTEC_h$) and non-technicians ($LNTEC_h$) according to benchmark data.

$$LUNSK_h = UNSKSHR_h \cdot LTOT_h . \tag{A31}$$

$$LTEC_h = TECSHR_h \cdot LTOT_h \tag{A32}$$

$$LNTEC_h = NTECSHR_h \cdot LTOT_h \tag{A33}$$

Government

A single government consumer represents government activities. The main activities of the government sector are to raise revenue through taxes and tariffs, provide a public good and transfer income. Government production is treated as a separate production sector, see the section on production. The level of government activities is held constant and exogenously given (*OKL*). Its budget constraint is accommodated through endogenous scaling of lump-sum transfers to households (*transfer*). The government budget constraint is described by

$$OKL = taxL + taxC + taxP - transfer , \tag{A34}$$

where *taxL, taxC* and *taxP* are tax income from labor, capital and production, respectively.

Investments and interest rate

Total capital stock and investments are exogenous in the model, and the interest rate adjusts such that the capital market clears.

Taxes and prices

Labor supply is subject to taxation, both through the social contribution fee, *tw*, paid by the employer and through income tax, *twm*, paid by households. Capital, the other input factor of production, is subject to a capital tax, *tc*.

Commodity taxes on inputs of production include VAT, other indirect commodity taxes and subsidies, energy tax, and carbon and sulfur taxes. Taxes on energy and environmental taxes are based on quantities and indexed by the GDP deflator, while the net of VAT, other indirect commodity taxes and subsidies are ad valorem. The prices of energy and material inputs in production including taxes are given by:

$$PE_{i,oil} = PD_{oil} \cdot (1 + itp_{oil}) + itpe_{oil,i} + itpSO2_{oil,i} + itpCO2_{oil,i} \tag{A35}$$

$$PE_{i,el} = PD_{el} \cdot (1 + itp_{el}) + itpe_{el,i} + itpSO2_{el,i} + itpCO2_{el,i} \tag{A36}$$

$$PE_{i,gas} = PD_{gas} \cdot (1 + itp_{gas}) + itpe_{gas,i} + itpSO2_{gas,i} + itpCO2_{gas,i} \tag{A37}$$

$$PE_{i,coal} = PD_{coal} \cdot (1 + itp_{coal}) + itpe_{coal,i} + itpSO2_{coal,i} + itpCO2_{coal,i} \tag{A38}$$

$$PE_{i,bio} = PD_{bio} \cdot (1 + itp_{bio}) + itpe_{bio,i} + itpSO2_{bio,i} + itpCO2_{bio,i} \tag{A39}$$

$$PM_i = \sum_{k \neq bio,coal,el,oil,gas} PD_k \cdot (1 + itp_k) \cdot insm_{k,i} \quad , \tag{A40}$$

where itp_{oil} is the ad valorem net tax on inputs of oil and $itpe_{oil,i}$, $itSO2_{oil,i}$, and $itCO2_{oil,i}$ are energy tax, sulfur tax, and carbon tax on oil, respectively. The energy tax and the environmental taxes are specific to various industries, so as to allow for tax exemptions.

Price of investments, PINV, is formed by the investment matrix, inv_i and the domestic producer good prices, PD_i, and the price of private goods, PHC_{fn} are transformed from producer good prices through a constant transformation matrix $a_{i,fn}$

$$PINV = \sum_i PD_i \cdot INV_i \tag{A41}$$

$$PHC_{fn} = \sum_i PD_i \cdot a_{i,fn} \quad . \tag{A42}$$

The tax base for VAT is assumed to mainly consist of private consumption, although other components of demand can be taxed. Private consumption is also subject to energy tax, $itce_{fn}$, carbon tax, $itcCO_{fn}$, sulfur tax, $itcSO2_{fn}$ and other indirect taxes and subsidies, $itci_{fn}$. The prices of consumer categories including taxes, $PHC2_{fn}$ are given by:

$$PHC2_{fn} = (1 + itcmoms_{fn}) \cdot (itce_{fn} + itcSO2_{fn} + itcCO2_{fn} + (1 + itci_{fn}) \cdot PHC_{fn}). \tag{A43}$$

This equation does not hold for transport modes used for work trips, however, where the value of time will be incorporated in the price facing the consumer

$$PHC2_{trw} = (1 + itcmoms_{trw}) \cdot (itce_{trw} + itcSO2_{trw} + itcCO2_{trw} + (1 + itci_{trw}) \cdot PHC_{trw}) + \alpha_{h,trw} PL_h, \tag{A44}$$

where PL_h is the net wage for households, h.

Price-cost balance

All production activities use constant returns to scale production technology, and there is free entry in all markets. Consequently, all activities make zero profit in equilibrium. The marginal cost of supply in sector i, mc_i, is defined by

$$\begin{aligned} mc_i Y_i = {} & PM_i IM_i + PE_{i,oil} OIL_i + PE_{i,gas} GAS_i + PE_{i,caol} COAL_i + PE_{i,bio} BIO_i + PC_i C_i + \\ & W_{i,tec} TEC_i + W_{i,ntec} NTEC_i + W_{i,usl} USL_i \end{aligned}, \tag{A45}$$

where $W_{i,tec}$ is the price of technicians and PC_i the price of capital.

The zero profit condition for the production of good i then becomes

$$mc_i Y_i = \sum_{pr} (PQ_{pr} Q_{pr} + PQ_{pr} EXP_{pr}) \cdot OUT_{i,pr}. \tag{A46}$$

In the Armington aggregation, the zero profit condition implies the gross value of Armington output to equal the cost of domestic inputs, plus the value of imports

$$PDZ_{pr} DZ_{pr} = PIMP_{pr} IMP_{pr} + PQ_{PR} Q_{pr}. \tag{A47}$$

Supply-demand balance

The equilibrium conditions simply state that demand equals the supply of production factors *LNTEC*, *LTEC*, *LNSK* and *CS*, since factor market prices are fully flexible

$$LNTEC = \sum_{i=1}^{18} NTEC_i. \tag{A48}$$

$$LTEC = \sum_{i=1}^{18} TEC_i. \tag{A49}$$

$$LNSK = \sum_{i=1}^{18} NSL_i \tag{A50}$$

$$CS = \sum_{i=1}^{18} C_i \,. \tag{A51}$$

All components of demand are measured at constant prices in basic values. Total domestic demand in basic values DZ_i for each commodity, except private services, is:

$$DZ_i = INSD_i + PK_i + INVS + LAS, \qquad i = 1,...,20, \tag{A52}$$

where $INSD_i$ is intermediate demand, PK_i household demand, $INVS$ total investments and LAS the exogenously given change in stocks.

To obtain total domestic demand also for private services, trade margins HMS must be added to the expression in equation A52.

Environment

Emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) originate from mobile and stationary sources within industries and households. However, the model also includes emissions from industry processes

The model evaluates the emissions of (CO_2), (SO_2) and (NO_x) as a function of energy use, and material input for industries and energy use for households. The total emissions of CO_2, SO_2 and NO_x in production are given by:

$$\begin{aligned} EM_{po} &= \sum_i emcoefoil_{po,i} \cdot oil_i + \sum_i emcoefgas_{po,i} \cdot gas_i + \\ &+ \sum_i emcoefbio_{po,i} \cdot bio_i + \sum_i emcoefcoal_{po,i} \cdot coal_i + \\ &+ \sum_i emcoefm_{po,i} \cdot M_i, \qquad po = CO_2, SO_2, NO_x, \end{aligned} \tag{A53}$$

where $emcoefoil_{po,i},...,emcoefm_{po,i}$ are coefficients for the emission of CO_2, SO_2 and NO_x in the use of energy carriers and materials in sector i. The total emissions of CO_2, SO_2 and NO_x by households are given by:

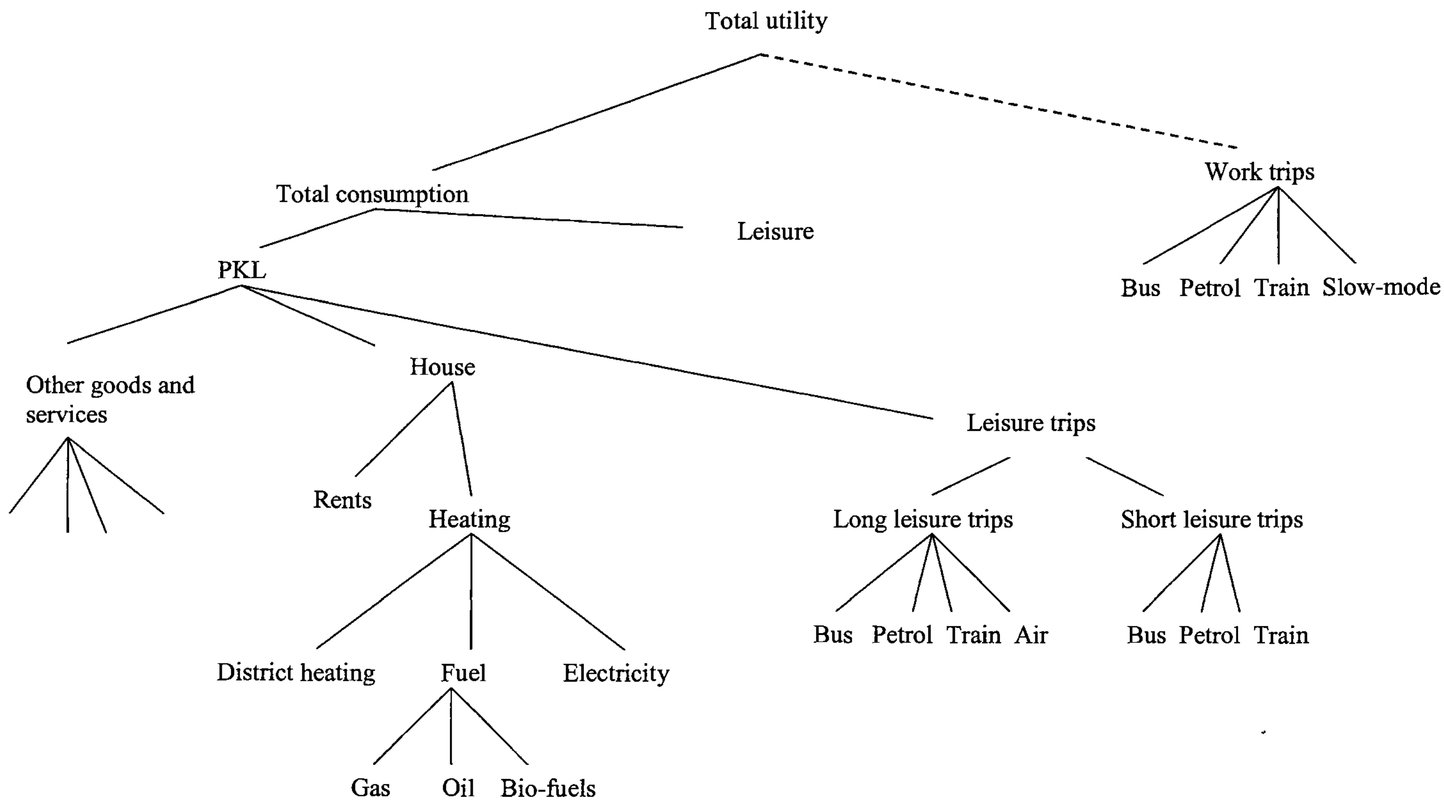
$$\begin{aligned} EMH_{po} &= emhcoefoil_{po} \cdot \sum_h HC_{h,oil} + emhcoefgas_{po} \cdot \sum_h HC_{h,gas} + \\ &+ emhcoefbio_{po} \cdot \sum_h HC_{h,bio} + emhcoefcoal_{po} \cdot \sum_h HC_{h,coal} \,, \end{aligned} \tag{A54}$$

$$po = CO_2, SO_2, NO_x,$$

where $emhcoefoil_{po}$ are the coefficients for emissions of CO_2, SO_2 and NO_x in private consumption when consuming oil.

Finally, the exchange rate is the numeraire and the foreign price level is set exogenously.

Figure A2. Household CES consumption function



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