ESSAYS ON ENVIRONMENTAL POLICY ANALYSIS: COMPUTABLE GENERAL EQUILIBRIUM APPROACHES APPLIED TO SWEDEN

Martin Hill

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Stockholm in December 2000

Martin Hill

Chapter I

Introduction and Summary

1. Introduction

This thesis consists of three essays within the field of applied environmental economics, all with the common basic aim of analyzing effects of Swedish environmental policy. Starting out from Swedish environmental goals, the thesis assesses a range of policy-related questions. The objective is to quantify policy outcomes by constructing and applying numerical models especially designed for environmental policy analysis. In short, static and dynamic multi-sectoral computable general equilibrium (CGE) models are developed in order to analyze the following issues:

(i) The costs and benefits of a domestic carbon dioxide (CO_2) tax reform. Special attention is given to how these costs and benefits depend on the structure of the tax system and, furthermore, how they depend on policy-induced changes in "secondary" pollutants.

(ii) The effects of allowing for emission permit trading through time when the domestic long-term environmental goal is specified in CO_2 stock terms.

(iii) The effects on long-term projected economic growth and welfare that are due to damages from emission flow and accumulation of "local pollutants", as well as the outcome of environmental policy when costs and benefits are considered in an integrated environmental-economic framework.

Using CGE models for environmental policy assessment

Environmental policy has largely been concerned with problems of local character. These problems can often be dealt with by using policies intervening at a local level with little or no economy-wide effects. Economic analysis of this type of problems can satisfactorily be treated within a partial equilibrium framework. Quite recently, the focus of environmental considerations has changed toward issues of nationwide or international character. This change has resulted in new policies that are likely to affect large parts of the economy, and are thus more appropriately analyzed within a general equilibrium framework.

Many economists have stressed the importance of analyzing issues related to environmental externalities within a general equilibrium framework.[1] Needless to say, a large number of important results have been derived using analytical general equilibrium models. However, the disadvantage of these models lies in the fact that they often become mathematically intractable whenever the model dimension approaches what could be regarded as satisfactory for a "realistic" policy analysis. In addition, analytical models have little to say about the *magnitude* of the various effects of environmental policy. These are the primary reasons for using multi-sector CGE models in the analysis.

CGE models are basically numerical applications of the general equilibrium theory formalized in the 1950's by Arrow, Debreu and others.[2] These numerical models are mainly suitable for quantitative analyses of the impact of non-marginal changes in an economy, and have the ability to use a high level of sectoral detail when studying effects of realistically specified policy scenarios. This makes it possible to account for effects of, for example, interaction between policy instruments, income distribution and trade issues, etc., which would be more or less impossible in an analytical model. Furthermore, the analysis can be carried out without having to abandon the conceptual framework suggested by general equilibrium theory and the theory of economic growth.

During the last decade, the application of CGE models to analyze environmental issues has become widespread. One of the reasons for this is an increasing awareness of environmental problems of non-local character, along with a gain in acceptance of economic instruments as tools for handling these problems. In addition, there is a strong demand from policymakers for quantification of the impacts from environmental policy reforms, which are often likely to have large and economy-wide effects. Hence, the CGE framework is particularly suitable for analysis of these types of reforms.

Two branches within environmental economic research have been particularly "CGE-intensive" in recent years. In the first branch, a variety of models has been constructed and used to assess the costs (and benefits) of global or multi-regional pursuits to reduce anthropogenic effects on global warming. These models have provided very valuable insights concerning, for example, interregional effects of different policy measures, long-term global adjustment issues, depletion of fossil fuels, etc. Although these models are becoming increasingly sophisticated, they still lack sectoral detail in their representation of individual

[1] Ayres and Kneese (1969) and Mäler (1974) were among the first to stress this. See also Mäler (1985).

[2] Introductions to CGE models are provided in e.g. Francois (1997) and Robinson et al. (1999). For a comprehensive description of the structure of CGE models see Ginsburgh and Keyzer (1997).

countries, and are therefore not suitable for studying impacts of country-specific environmental policies in small economies.[3]

The second branch is concerned with regional or country-specific environmental policy reforms. In general, these studies assess the impact of unilateral pursuits to abate pollution. Numerous effects from such reforms have been studied, including equity, trade, and employment effects with regard to, for example, the design and scope of the policy instruments. From these studies it is clear that the impact of environmental policy depends heavily on the type of economic instrument used and how it interacts with, for example, the preexisting tax system.[4] Consequently, when analyzing these issues, it is preferable to use a relatively detailed specification of the economy. Most studies of unilateral policy reforms thus apply multi-sectoral single or multi-country models.

Policies and models in this thesis

The policy questions analyzed in this thesis fall into the second branch of this "CGE-intensive" research. Since the purpose of the studies is to assess Swedish unilateral policies, the models constructed are of single-country type. Clearly, many effects of Swedish policies could be studied more accurately in a multi-country framework. However, multi-country models have several drawbacks. For example, data restrictions often make it impossible to account for many country-specific characteristics reflected in the data for the domestic economy. Furthermore, if the model is to provide enough detail, it will be very difficult to handle, especially if dynamic effects are to be assessed. Thus, there is a trade-off between the use of multi-country and single-country models. Given the objective of the essays in this thesis, single-country models are preferable.

The first and second essays analyze Swedish unilateral pursuits to reduce the domestic contributions to global warming. Since the cost of green house gas abatement could be substantial while the benefits are highly uncertain, it is difficult for a policymaker to motivate the implementation of such environmental policies. This is especially true if a small open economy has the ambitions to "take the lead" and impose measures to reduce domestic emissions ahead and independent of pursuits in other countries. The two essays consider different aspects affecting the costs of attaining domestic climate policy goals.

[3] Clearly, global CGE models are not a homogeneous group of models. The models characteristics differ substantially and range from highly aggregated models such as the RICE model (Nordhaus and Yang, 1996) to disaggregated multi-sector models such as the G-Cubed model (McKibbin and Wilcoxen, 1999).
[4] See e.g. Goulder (1995) and Bouvenberg (1999) for surveys.

In the policy debate, several arguments have been brought forward to stress that abating green house gas emissions might not be very costly. For example, if an emission tax is used, recycling of tax revenues through lowering of preexisting (distortionary) taxes may substantially reduce the cost of abatement. Further, large adjustment costs that could result from emission taxes might be mitigated if "sensitive" sectors are exempted from the policy. Another argument recognizes the benefits from reductions of other "secondary pollutants" that will be reduced as a result of green house gas policy.

Based on these arguments, the first essay (*chapter II*) aims at assessing structural effects and the net and gross welfare impact of unilateral Swedish efforts to reduce domestic CO_2 emissions. Analyzing the net welfare effects requires quantification of "secondary" emissions that, to a large extent, are sector-specific. Assessment of environmental policy-induced changes in the industrial structure necessitates relatively detailed calculations of the emissions from each sector. Furthermore, the welfare cost of the policy depends on the structure of the preexisting tax system. Thus, the "interaction" between taxes should be taken into consideration. In addition, if the policy instruments raise revenues, these can be "recycled" in various ways such as through sector-specific subsidies etc. Consequently, to consider these effects, the model constructed must be multi-sectoral, with an emphasis on the representation of the tax system and sectoral emission structure.

Another issue in the policy debate is the timing of emission reductions. Given that the environmental goal is to reduce the contribution to global warming, and that this in turn is a pollution stock related problem, policymakers should consider the cost of using different abatement paths. If the long-term policy goal is specified as a reduction in the pollution stock, it is clear that postponing abatement necessitates larger abatements in the future. On the other hand, by postponing abatement, polluters are given more time to adapt and the adjustment cost could thereby be reduced. Thus, the objective of the second essay (*chapter III*) is to study issues related the use of policy instruments with a temporal dimension. More specifically, the aim is to assess the effects of allowing for intra-sectorally and intertemporally emission permit trading, when the Swedish long-term environmental goal is specified in CO_2 stock terms. To enable analysis of welfare as well as structural effects of such policy instruments, it is necessary to construct a multi-sectoral and fully dynamic model in which the intertemporal permit trade is explicitly represented.

Finally, the third essay (*chapter IV*) is concerned with environmental policies aiming at reducing the effects of "local pollutants". The abatement of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) is among the main goals of Swedish environmental policy. This is also reflected by the effort to quantify the effects these emissions have on Sweden, which is undertaken within the work on establishing Swedish environmental and economic accounts.[5] Policies aiming at reducing these emissions can take different forms, but should clearly take potential benefits into account. Furthermore, given that these emissions affect economic variables, policy-induced costs and benefits should ideally be assessed in an integrated framework. The principle goal in the third essay is therefore to quantify environmental policy impacts in a fully integrated framework that includes environmental damage relationships as well as different means of counteracting these effects. In the analysis, impact that emission flow and accumulation have on primary resources used in production and consumption is considered. Some of these damages are sector-specific and, furthermore, functions of the accumulated level of pollution. Among other concerns, this necessitates the construction of a dynamic multi-sectoral model that endogenizes the dynamic and sector-specific damage relations.

Although largely based on well-known general equilibrium theory, there is a risk that results from numerical general equilibrium models become difficult to interpret for the reader and, thus the model becomes a "black box", especially if the model documentation is scarce. To avoid this, *chapter V* provides a more detailed algebraic description of the dynamic model extended and applied in chapters III and IV. The chapter also includes illustrative simulations and sensitivity tests aiming at bringing attention to the importance of some of the model assumptions.

Contributions of this thesis

Clearly, this is not the first CGE assessment of Swedish environmental policy. Bergman (1996) studies terms of trade effects in relation to unilateral CO_2 tax exemption rules. Nilsson (1999) uses a multi-country model to assess the impact on Sweden in the case of Swedish vs. European implementation of CO_2 taxes, while Harrison and Kriström (1999) assess structural and in income distribution effects of CO_2 taxes. Although these studies partly analyze issues related to those considered in the first essay of this thesis, they largely focus on other effects of CO_2 policy. Consequently, they apply models not suitable for assessing many of the issues considered here.

One such issue, examined in the first essay, is the policy-induced effect on secondary emissions which, in turn, enables the quantification of net benefits of different policy reforms. Furthermore, earlier Swedish multi-sectoral models have all been static or iterative dynamic, and hence, unable to assess dynamic aspects considered in the second and third essay. The

[5] See e.g. NIER (1994)

contribution of the second essay is to empirically assess policy effects of intra- and intertemporal emission permit trade within a fully dynamic multi-sectoral framework.

Few applied general equilibrium studies have studied environmental policies in a fully integrated environmental-economic framework. Bergman et al. (1995) include some such interactions into an iterative dynamic model to compare different definitions of "green" net national product. The third essay in this thesis extends this work and provides an assessment of environmental policies in a dynamic, multi-sectoral model where several environmental-economic relationships are endogenized.

To summarize, by extending previous work on Swedish environmental policy, this thesis aims at contributing to a better understanding of the static as well as dynamic effects of the design of policy instruments. Evidently, the results presented are mainly of interest for Swedish policy but can, together with studies of other countries, also contribute to deeper understanding of the effects from environmental policy reforms in general.

2. Summary of the essays

2.1 Essay 1 – Green Tax Reform: The Second Dividend, Secondary Benefits and the Effect of Tax Exemptions

Increasing concern for global climate change has created a demand for actions to curb emissions of carbon dioxide (CO_2). Significant reduction of these emissions is, however, likely to impose large costs, especially if it concerns a unilateral pursuit by a small open economy such as Sweden. Given that the benefits of abating CO_2 emissions are highly uncertain, it is difficult for a policymaker to motivate the implementation of such environmental policies. There are, however, some arguments that have been brought forward in the policy debate, suggesting that unilateral national CO_2 abatement policies should be carried out even if the magnitude of environmental benefits are uncertain.

One argument is based on the observation that environmental taxes may improve economic efficiency by reducing distortions present in the existing tax system. If correctly designed, such taxes may create the necessary incentives for emission abatement and simultaneously raise revenues that can be used to reduce other (distorting) taxes. Thereby, the (gross) cost of the environmental policy can be decreased. A large part of the recent literature on environmental taxes has analyzed this so-called second dividend of environmental taxes[6] and, in many countries, it has been used as an argument in favor of unilaterally pursuing CO_2 tax

[6] See Goulder (1995) and Bovenberg (1999) for surveys.

reforms. If the second dividend is sufficiently large, CO_2 abatement could actually be beneficial, regardless of the environmental benefits.

Due to the lack of internationally coordinated actions, a unilateral reduction of environmentally damaging activities is likely to involve large adjustment costs from, for example, adverse effects on international competitiveness in energy and export intensive industries. Evidently, this is an argument against unilateral policy reforms. However, these costs do not necessarily have to be large if a proper sectoral tax differentiation is used.[7]

Another distinct argument for justifying a CO_2 tax reform is its effect on "secondary emissions". Reducing the burning of fossil fuels will also reduce emissions of other pollutants. The reduction of these pollutants might bring about "secondary" benefits that are large enough to motivate relatively high CO_2 taxes.[8]

General equilibrium theory has been very useful in clarifying many of the effects of environmental policy reforms. The theoretical work, however, indicates that many of the effects have contrasting impacts, which leaves a number of questions that can only be answered empirically.[9] This essay studies several aspects of CO_2 taxation in Sweden and the basic aim is to extend and complement some of the previous work on these issues. Some of the questions this essay tries to answer are:

- What difference does it make for the gross cost of domestic CO_2 reductions if taxes are used instead of a non-revenue-raising instrument?
- Can CO_2 taxation be motivated by the "secondary" environmental benefits they entail as they reduce fossil fuel consumption?
- How does the net and gross cost of the tax reform change if some sectors in the economy are exempted from full CO_2 taxation?

The answers to these questions largely depend on how the preexisting tax system is designed and how fossil fuel consumption differs between sectors. This motivates the use of a disaggregated numerical model where the tax system, energy use and sector-specific emission, are explicitly modeled. In addition, it is also necessary to include the monetary valuation of changes in emission levels.

To accomplish this, a static computable general equilibrium model is constructed that monetizes the costs and quantifies the pollution levels of different environmental policies. Quantification of "secondary emission effects" from CO_2 policies, especially those resulting

[7] See e.g. Bergman (1996) for empirical support for this.
[8] Empirical support for this is presented in Boyd et al. (1995), Ekins (1996) and Brendemoen and Vennemo (1996).
[9] See e.g. Bovenberg and de Mooij (1994) and Parry (1995).

from tax scheme induced changes in the industrial structure, becomes possible by including relatively detailed calculations of the emissions from each sector. These figures together with separable benefit estimates of reduced pollution yield net cost estimates of the tax reform.

The results indicate that by "recycling" the CO_2 tax revenue through reduced payroll taxes, the marginal welfare cost of CO_2 abatement can be considerably reduced in relation to the cost of using a non-revenue-raising instrument. The total cost of the benchmark year CO_2 tax system is significantly increased by the use of tax exemptions on "sensitive industries". Furthermore, the marginal welfare cost of emission reductions is substantially decreased if the sectorally differentiated CO_2 tax is replaced by a uniform CO_2 tax. In addition, the adverse effects on employment resulting from uniform taxation cannot motivate the use of exemptions. These effects can be mitigated at a lower cost by using direct labor subsidies on the affected sectors. Finally, the value of policy-induced changes in "secondary emissions" cannot justify increased CO_2 taxation unless the marginal valuation of reduced CO_2 emissions exceeds 320 SEK_{93} per ton.

2.2 Essay 2 – Bankable Emission Permits and the Control of Accumulative Pollution: A Numerical Application to Swedish CO_2 Policy

There is a general consensus among economist that tradable emission permit systems can be an efficient strategy for achieving environmental goals. Allowing permits to be transferable among polluters results in an equalization of marginal abatement costs between pollution sources. Montgomery (1972) proved that in a competitive economy such a permit system can achieve a given emission standard at least abatement cost. Cronshaw and Kruse (1996) and Rubin (1996) extended Montgomery's work by considering intertemporal permit trade, and showed that many of the properties carried over into trading through time. Although intertemporal emission permits trading, i.e. permit banking and borrowing, is regarded as one of the major components of emission trading systems, few empirical studies have considered the potential efficiency gain resulting from allowing for full or restricted trading through time.

The growing concern about global climate change and the importance of controlling anthropogenic carbon dioxide (CO_2) emissions, have resulted in numerous policy proposals suggesting tradable CO_2 permits. Most of the proposals recognize international emission permit trading as an effective means of reducing global emissions, especially due to large international differences in abatement costs and the irrelevance of where the emissions take place. Although global CO_2 permit trade is likely to efficiently reduce abatement costs, it is questionable if such a system will be implemented within the near future, and instead a number of country- or region-specific systems have been proposed.[10] Some of these proposals recognize the possibility to use "bankable" permits.

This study uses a dynamic, multi-sectoral, CGE model to analyze a unilateral Swedish pursuit, where the environmental policy goal is to reduce the Swedish contribution to global warming, i.e. to the accumulation of green house gases in the atmosphere, by the use of tradable CO_2 emission permits. The main objective is to analyze the effects on the abatement path, permit price and the potential efficiency gains from allowing permits to be tradable through time with a given future pollution stock reduction target. In particular, an annual emission cap policy is compared with policies where permit borrowing and/or banking is allowed, and where each policy aims at attaining the same "long-term" pollution stock target.

The results suggest that, compared to a constant annual emission cap, allowing for permit banking and borrowing will result in a relatively modest reduction of the aggregate welfare cost. The abatement path will, however, be noticeably different for the various policies. For example, due to the positive shadow cost of the pollution stock, relatively large emission reductions will be undertaken in the early years if banking is allowed. This will be beneficial despite the presence of large rigidities in production technology that are due to large share of pre-policy installed capital. Allowing for borrowing will result in a somewhat larger abatement in the final periods. In addition, the effect of availability of (subsidized) wind power electricity production is also considered. If such technology is available, the shadow cost of the pollution stock is reduced if permit borrowing is allowed, and will therefore result in less abatement in early periods.

2.3 Essay 3 – Assessing Effects of Pollution and Environmental Policy in an Integrated CGE Framework

Emissions and accumulation of pollutants, with few exceptions, have both direct and indirect negative effects on welfare. The direct effects are due to the negative impact on the consumption value of the environment, while the indirect effects stem from the negative impact on primary resources used in the production process. In other words, pollution has feedback effects on the rate and pattern of economic growth. Moreover, if these feedback effects are neglected in numerical models, both environmental policy evaluations and long-term economic projections based on these models will be biased. Many economists have stressed the importance of including these economic-environmental links into a general

[10] See e.g. Haites et al. (2000)

equilibrium framework. However, only a few studies that include such effects in multi-sectoral CGE models can be found in the literature.[11]

The purpose of this study is to elucidate direct and indirect feedback effects of SO_2 and NO_x emissions on productivity, economic growth and welfare within the frame of a dynamic, multi-sectoral, CGE model of the Swedish economy. The basic aim is to develop a model framework for environmental policy evaluation where costs and benefits are integrated. The economic-environmental relationships are primarily based on data from the work on environmental and economic accounting carried out at the Swedish National Institute for Economic Research and Statistics Sweden. These data allow for rough specifications of some key damage functions, as well as defensive activities to be explicitly included in the model.

The simulation results suggest that the direct and indirect effects of the pollutants over the next few decades will have a non-negligible negative impact on welfare and GDP. However, in terms of the overall rate and pattern of economic growth, CGE models with and without endogenous feedback effects produce very similar results. That is, the bias in the long-term economic projection from the local pollutants considered is relatively modest. The effects of emission tax policies are also considered in this integrated framework. The results indicate that the positive productivity and welfare effects of the resulting emission reductions are smaller than the cost of attaining them by means of a revenue neutral fossil fuel tax. Clearly, due to the large emission "imported" into Sweden, policy benefits are highly dependent on whether the policy is a unilateral pursuit or the result of an international agreement that also involves reduction in neighboring countries. However, assuming proportional emission reduction from foreign sources, as if the policy would be part of an international agreement, do not justify the fossil fuel tax policy. Important assumptions underlying these results are the availability of other defensive measures to counteract the damages.

[11] See e.g. Bergman et al. (1995) and Vennemo (1997).

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Chapter II

Green Tax Reform: The Second Dividend, Secondary Benefits and the Effect of Tax Exemptions*

1. Introduction

Increasing concern for global climate change has created a demand for actions to curb emissions of carbon dioxide (CO_2). Significant reduction of these emissions is, however, likely to impose large costs, especially if it concerns a unilateral pursuit by a small open economy such as Sweden. Given that the benefits of abating CO_2 emissions are highly uncertain, it is difficult for a policymaker to motivate the implementation of such environmental policies. There are, however, some arguments that have been brought forward in the debate suggesting that unilateral national CO_2 abatement policies should be carried out even if environmental benefits are uncertain.

One argument is based on the observation that environmental taxes may improve economic efficiency by reducing inefficiencies in the existing tax system. If correctly designed, such taxes may create the necessary incentives for emission abatement and simultaneously raise revenues that can be used to reduce other (distortionary) taxes. Thereby, the cost[1] of the environmental policy can be decreased. A large part of the recent literature on environmental taxes has analyzed this so-called second dividend of environmental taxes,[2] and, in many countries, it has been used as an argument in favor of unilaterally pursuing CO_2 tax reforms. If the second dividend is sufficiently large, CO_2 abatement could actually be beneficial, regardless of the environmental benefits.

Due to the lack of internationally coordinated actions, a unilateral reduction of environmentally damaging activities is likely to involve large adjustment costs from adverse effects on international competitiveness in energy and export intensive industries. Evidently, this is an argument against unilateral policy reforms. However, these costs do not necessarily

* This chapter is a revised and extended version of Hill (1999).

[1] Unless otherwise indicated, "cost" refers to the gross cost, i.e. excluding the benefits that might occur due to changes in pollution levels. "Net cost" refers to the cost less the value of environmental benefits from reduced pollution levels.

[2] See e.g. Pearce (1991), Bovenberg and de Mooij (1994), Goulder (1996) and Starret (1999).

have to be large if a proper sectoral tax differentiation is used.[3] Tax differentiation could also be justified by "pollution leakage" which occurs when export and energy intensive sectors move their production to countries with lower environmental taxes. In the case of globally damaging pollutants such as green house gases, this leakage-effect could substantially reduce the effectiveness of unilateral action.

Another distinct argument for justifying a CO_2 tax reform is its effect on "secondary emissions". Reducing the burning of fossil fuels will also reduce emissions of other pollutants. The reduction of these pollutants might bring about "secondary" benefits that are large enough to motivate relatively high CO_2 taxes.[4]

The purpose of this study can be divided into three parts, all related to the arguments for unilateral abatement of CO_2 as discussed above. First, the study analyzes the cost of unilateral efforts to reduce Swedish CO_2 emissions, and further, how large the gain from using taxes instead of non-revenue raising instruments are. Second, it assesses the use of sectorally differentiated taxes to avoid large adjustment costs. If tax exemptions are justified by protection of employment in sensitive industries, how effective are they compared to the use of other instruments to accomplish this goal? Third, the "net cost", i.e. the cost less benefits from secondary emission reductions, of an environmental tax reform is quantified.

To accomplish this, a static computable general equilibrium (CGE) model is constructed, which monetizes the costs and quantifies the pollution levels of different environmental policies. Quantification of "secondary emission effects" from CO_2 policies, especially those resulting from tax scheme induced changes in the industrial structure, are enabled by including relatively detailed calculations of the emission from each sector. These figures, together with separable benefit estimates of reduced pollution, yield net cost estimates of the tax reform.

The rest of the paper is organized as follows. Section 2 briefly reviews the debate on the "double dividend" of environmental taxation and discusses potential effects of tax exemptions. Section 3 describes the model used to assess the Swedish tax reform. A description of the policy scenarios considered together with the simulation results then follows in section 4. A sensitivity analysis of these results is undertaken in section 5 and finally, section 6 concludes the study.

[3] See e.g. Bergman (1996) for empirical support for this.
[4] Empirical support for this is presented in Ekins (1996), Boyd et al.(1995), and Brendemoen and Vennemo (1996).

2. Effects of a green tax reform

In a perfect market economy with lump-sum transfers, an efficient environmental tax will equal the marginal external effect of pollution, and the tax revenue returned lump-sum. In such an economy, an efficient outcome can also be obtained by the use of non-revenue raising instruments, such as freely distributed tradable emission quotas. In a second-best economy, however, the optimal tax rate would typically deviate from this first-best level and the non-revenue-raising instrument will be sub-optimal. The basic argument for the superiority of the use of taxes instead of an emission quota is that the tax raises revenue that could be used to reduce existing distortionary taxes. That is, there exists a (second) dividend other than the environmental improvement, if taxes are used.

This "double dividend" was noted by, for example, Pearce (1991). He defined the second dividend as positive if the revenue raised by the environmental tax could be used to reduce distortions in the tax system.[5] Goulder (1995) clarified the different interpretations of this second dividend, by distinguishing between two main forms of the double dividend: the weak and the strong form. In the weak double dividend claim, a positive second dividend exists if the environmental tax can finance a reduction of a distortionary tax such that the cost of the environmental tax is lower relative to the cost that would occur if the revenue were returned to the economy lump-sum. The strong form states that a double dividend exists if a revenue neutral substitution of the environmental tax and a "typical" or "representative" distortionary tax yield a non-negative welfare cost.[6]

Much of the debate has centered on the existence of the strong form of the double dividend, which has been pointed out by, for example, Goulder (1995) as being highly attractive to policymakers due to large uncertainties of the value of emission reductions. If there exists a strong double dividend, then it suffices to know that the environmental benefits from reduced emissions are non-negative. Several theoretical studies have, however, indicated that the existence of the strong double dividend is unlikely (e.g. Parry (1995), Starret (1999), Bovenberg and de Mooij (1994)). In these studies, the so-called "tax interaction effect" exceeds the "revenue recycling effect" under plausible assumptions.[7] The results, however,

[5] Other definitions of the double dividend exist in the literature such as the "employment double dividend", were the effects on employment levels are positive when the revenues are recycled through lowering of labor taxes; see e.g. Carraro et.al. (1996).

[6] Goulder (1995) also defines an "intermediate" form of the double dividend, which is identical to the "strong" form except that there is no requirement that the distortionary tax should be a "typical tax".

[7] In Goulder (1995), the "revenue recycling effect" is defined as the welfare increase from using environmental tax revenues to cut pre-existing distortionary taxes relative to returning the revenues lump-sum. The "tax interaction effect" (or the interdependency effect defined by Parry (1995)) is the potential exacerbation of pre-

depend heavily on the pre-existing distortions in the tax system. For example, if the tax system is characterized by large differences in marginal excess burdens (MEB), i.e. large differences in the excess welfare cost from raising one marginal unit of public funds between different tax instruments, there is a greater potential for a decreased cost of the environmental tax.[8] However, if the burden of the environmental tax falls largely on labor, which might be the case with, for example, a gasoline tax, then distortions in the labor-leisure choice could exacerbate rather then reduce pre-existing tax distortions, thereby resulting in a costlier tax reform (Bovenberg and de Mooij (1994), Parry (1995)).

These results imply that in a second-best world, the environmental tax should be lower than the optimal tax in a first best setting. Because the "tax interaction effect", e.g. the adverse effect on the labor-leisure choice, also is present if a non-revenue raising instrument is used, this also implies that there may not be any net efficiency improvement from the use of such instruments to reduce emissions. Important assumptions underlying these results are that the uncompensated labor supply elasticity is positive and polluting commodities are greater than average substitutes for leisure.

In general, empirical studies of environmental taxation conclude that the weak form of the double dividend hypothesis is true, i.e. the revenue recycling effect is positive. Although several studies indicate that the welfare gain from recycling the revenue could be substantial due to large MEB of e.g. labor taxes[9], most studies using CGE models find that there is a positive cost from revenue neutral tax reforms. Jorgensen and Wilcoxen (1993), however, conclude that the introduction of a revenue neutral CO_2 tax in the US could yield a strong double dividend due to high MEB of capital taxation. Studies of tax reforms in European countries generally find no support for the strong double dividend hypothesis. That is, the pre-existing differences in MEB in these countries are not large enough to make the reform costless.[10]

Needless to say, the MEB of environmental taxes depends, to a large extent, on the design of the environmental tax system. For example, the use of environmental tax exemptions on specific energy and export intensive sectors implies that the usually narrow tax base for environmental taxes will be further narrowed. Therefore, the environmental tax scheme is

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existing tax distortions caused by the environmental tax when it disturbs the labor-leisure choice or the savings-consumption choice.

[8] It follows that if the marginal excess burden is equalized across pre-tax reform taxes, then the environmental tax cannot have a second dividend that exceeds the cost of introducing the tax to decrease the environmental externality. This is pointed out by e.g. Bohm (1997).

[9] See e.g. Goulder et. al (1997) and Bouvenberg and Goulder (1996).

[10] See e.g. Böhringer et.al. (1997) and Harrison and Kriström (1999).

likely to carry a relatively higher excess burden than would otherwise be the case.[11] Goulder (1995) thus concludes that the prospect for a positive second dividend is greater if the environmental tax base is broad. This, clearly, speaks against the use of tax exemptions. However, several effects have been put forward to the advantage of a tax scheme with exemptions. For example, exemptions reduce the "pollution leakage effect" that occurs when energy intensive production is relocated abroad. Using exemptions may also reduce the potentially large adjustment costs due to policy-induced output reductions resulting in idle capital and unemployment.

To avoid these effects, all countries that have introduced CO_2 taxes are currently using tax policies designed to mitigate the impact on some of their domestic energy intensive industry that faces international competition. This includes Sweden, which introduced a CO_2 tax on fossil fuels as part of a wider tax reform in 1991. Since 1993, a large part of the Swedish export intensive industry only pays one-fourth of the CO_2 tax for competitive reasons.[12]

Using these exemptions clearly implies that, for a given domestic emission reduction target, the tax burden on non-exempted fossil fuel consumers must increase. Typically, non-exempted fossil fuel users have a different consumption structure; e.g. they consume more gasoline and diesel fuel and less coal and heavy fuel oil relative to the exempted industries. By studying the fossil fuel input structure of exempted and non-exempted industries in Sweden, it is clear that the current CO_2 tax falls primarily on gasoline, diesel and light fuel oil while coal and heavy fuel oil to a large extent escape the tax.[13] Due to these differences in consumption patterns, the use of CO_2 tax exemptions is likely to have indirect effects on the emissions of other fossil fuel related pollutants. For example, in 1993 the exempted industries in Sweden emitted 28 percent of the total CO_2 emission, 49 percent of the sulfur dioxide (SO_2) total but only 12 percent of the nitrogen oxides (NO_x). Hence, for a given CO_2 emission level, a removal of the exemptions is likely to have an effect on these "secondary" emissions. This could be important when assessing the net cost from the use of CO_2 tax exemptions, i.e. the cost including environmental benefits. The current fossil fuel tax scheme with lower tax

[11] This is supported by results from an empirical assessment of a tax reform of Germany, where Böhringer and Rutherford (1997) find that the use of tax exemptions significantly increases the cost of environmental tax policy.

[12] In Appendix 1, the exempted sectors are shown together with benchmark output, emissions and tax levels (See also Table 3.1). For a more complete description of the use of environmental taxes in Sweden, see e.g. Brännlund (1997).

[13] In 1993, the benchmark year in the simulations, the exempted industries' consumption of coal and heavy fuel oil was 76 and 36 percent of total consumption, respectively. Their consumption of gasoline, diesel and light fuel oil was 11, 4 and 12 percent, respectively (SCB, 1996).

on the heavy industry might, for example, be (more) justified if emission reduction goals for secondary pollutants are taken into consideration.

In summary, the discussion in this section points at two issues that will be studied in the following sections of the paper. First, the magnitude of the second dividend of an environmental tax reform depends on the (differences in) marginal excess burdens in the preexisting tax system. The use of tax exemptions changes the incidence of the environmental tax, and will most likely increase the cost for a given environmental target and, hence, reduce the likelihood of a (strong) double dividend result. Removal of tax exemptions might, however, cause large adjustment costs in certain industries that should be considered. Second, an environmental tax reform aiming at reducing CO_2 emissions will inevitably affect the emission of other damaging pollutants. Two different policy designs, e.g. with or without tax exemptions, will probably affect these other pollutants differently, and therefore have unequal effects on the first (environmental) dividend of the environmental tax reform. It is therefore important to consider a wide range of pollutants when evaluating the net cost of different policy designs. The next section presents a simulation model capable of assessing these issues.

3. The model

The model used for the simulations is a static, small open economy, computable general equilibrium model designed to investigate energy and environmental policies. An algebraic model formulation and description of the data used, along with the exogenous parameter values, are presented in Appendices 1 and 2.

Although the basic structure of this model falls well within the mainstream CGE models in the literature, it differs in several ways from CGE models applied in earlier studies of environmental policy in Sweden.[14] Most important, the model includes an energy input structure that is relatively more disaggregated and therefore facilitates simulations where substitution possibilities among energy inputs are possible. The disaggregation, in turn, enables a more realistic specification of energy/environmental taxes, and a more precise calculation of changes in emissions, which is important when considering secondary effects from e.g. sulfur dioxide and nitrogen oxides, especially if the policy induces large structural changes in the economy.

[14] See e.g. Bergman (1996) and Harrison and Kriström (1999).

3.1 The basic model structure

Goods are produced using primary factors and intermediate inputs. The output is sold in perfectly competitive markets where producers behave according to standard neoclassical microeconomic theory, maximizing their profits taking market prices as given. Production technology in all sectors exhibit constant returns to scale and is characterized by nested constant elasticity of substitution (CES) production functions (see Figure 3.1). The nesting structure chosen for the model is relatively common in CGE models used for energy-environmental related policy evaluations and is the structure proposed by, among others, Burniaux et al. (1991) and Kemfert and Welch (1997).

The top level is a Leontief nest where the producers (indexed j) use different non-energy intermediate goods, A_{ij}, and an aggregate of energy goods and primary factors, LKE_j, in fixed proportions,

$$Y_j = Y_j\left(A_{1j},\ldots,A_{nj},LKE_j\right), \tag{1}$$

where

$$LKE_j = LKE_j\left(L_j\left(LU_j,LS_j\right),KE_j\left(K_j,E_j\right)\right). \tag{2}$$

K_j, LU_j and LS_j denote capital, unskilled and skilled labor, respectively, and E_j a CES aggregate of different energy inputs. All nests except the top level have elasticities greater than zero, reflecting a higher degree of substitutability between different primary factors and energy input, and between different types of energy goods. The total domestic use of primary factors, skilled and unskilled labor and capital, is fixed at the benchmark levels but is assumed to be perfectly mobile between sectors within domestic borders.[15]

Output from sectors, Y_j, is transformed into goods using a Leontief technology. These are, in turn, is transformed into goods destined for the domestic market and goods destined for the export market using a constant elasticity of transformation technology.[16]

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[15] The assumption of intersectorally perfectly mobile capital is relaxed in the sensitivity analysis, where a CES nest with sector-specific and inter-sectorally mobile capital replaces Kj.

[16] Outputs from mining and petroleum industries are modeled slightly differently. These industries produce two outputs using a constant elasticity of transformation technology. The petroleum industry first chooses the amount of heavy fuel oil and other petroleum products to be produced, and, in a second stage, the amount of these goods that should be destined for the export and domestic market. That is, they use a two level constant elasticity of transformation frontier. The mining industry has the same output structure, but produces coal (and coke) and other mining products.

The final demand by private households is modeled through a representative agent with preferences represented by a nested CES utility function

$$U = U\big(PC(E,C), L(LU_C, LS_C)\big). \tag{3}$$

The consumer first decides how to allocate his income between consumption, PC, and (CES composite) leisure, L. At the second level, the choice is between a composite of non-energy goods, C, and a composite of energy goods, E. Finally, the private consumer decides how much to spend on different energy goods and on different non-energy goods. The household income available for consumption consists of payments received from the sale of primary factors plus transfers from the government, minus the exogenously fixed private investment. The consumer has the possibility to consume his labor endowment as leisure or supply it at the clearing labor market, i.e. unemployment is modeled as "voluntary".[17]

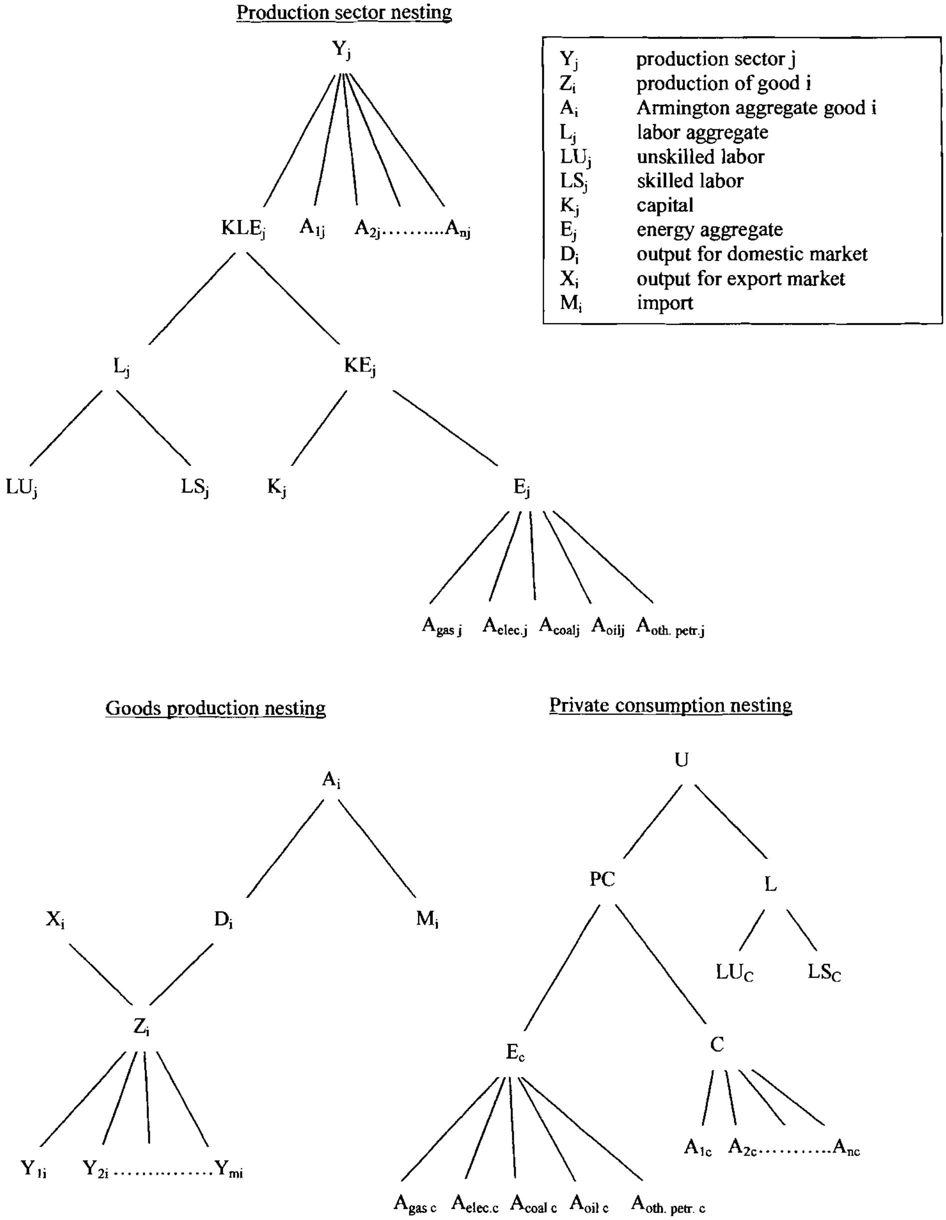
The government expenditure is modeled as a two-level CES function, where the top level is a Leontief nest in which the government allocates its income in fixed proportions between different non-energy goods and an energy aggregate. In the energy nest, the government can choose between the different energy goods. Government aggregate consumption and investment are exogenously fixed at the benchmark level in all scenarios. The expenditures are funded by net tax and tariff revenues.

Goods for final consumption as well as intermediate inputs in production, A_i, are modeled as a CES aggregate of domestically produced and imported inputs. These inputs are assumed to be imperfect substitutes according to the so-called Armington assumption (Armington, 1969). In the model, the assumed Armington elasticities do not depend on the user of the aggregate good. That is, the relative composition of imported and domestically produced goods will be the same for all users.

Since Sweden is regarded as a small open economy in this model, Swedish imports and exports have no effect on international prices. Hence, the import supply and export demand curves are horizontal at the exogenously fixed international prices. The model closes through balancing of the current account by adjusting the "real exchange rate", taking into account exogenously specified capital inflows.

[17] Note that the consumer can chose between consuming "unskilled" and "skilled" leisure. This specification will result in higher labor type specific supply elasticity, relative the aggregate labor supply elasticity. That is, the possibility to substitute skilled leisure for unskilled leisure (and vice versa) increases the supply sensitivity to labor-type specific price changes.

Figure 3.1 Nesting structures.



3.2 Details of the model

The model is calibrated to fit benchmark data for the year 1993. The input-output data is disaggregated into 47 sectors, but the number of sectors in this model is restricted by reliable data on emissions and energy use. This restriction allows for a disaggregation level of 17 sectors to match the environmental and economic accounts of Sweden. In these accounts, sectors are aggregated in such a way that they should be fairly homogenous with respect to their emissions. The sectors produce 19 different goods, 14 non-energy goods and 5 energy goods. The energy goods are gas, electricity, coal, heavy fuel oil and "other petroleum fuels". The division of energy goods into these categories matches differences in benchmark environmental taxation on fossil fuels. All sectors and goods are shown in Table 3.1 below. Note that most sectors and goods have the same model name, although there is no one to one correspondence between them. For most goods, however, the relationship is "almost" one to one.

Table 3.1 Industries and good categories

Industries	Goods
Agriculture	Agriculture
Forestry	Forestry
Fishing	Fishing
Food and Textile[a]	Food and textile
Pulp and Paper[a]	Pulp and paper
Chemical[a]	Chemical
Steel and Metal[a]	Steel and metal
Manufacturing[a]	Manufacturing
Water and Sewage	Water and sewage
Construction	Construction
Transport	Transport
Trade and Services	Trade and services
Dwelling	Dwelling
Electricity and Heating	Other mining products
Gas	Electricity and heating
Petroleum[a]	Coal and coke
Mining[a]	Heavy fuel oil
	Other petroleum fuels
	Gas

[a] These sectors are levied lower CO_2 taxes in the benchmark year (see Appendix 1 for details).

There are 11 different (ad valorem) taxes in the model, including 5 different energy and environmental taxes. The taxes on primary factors are tax on capital, payroll tax, and income tax on the use of skilled and unskilled labor. A general value added tax is levied on all produced goods, and some goods are levied a "special good tax" (or subsidy). Imports are levied an import tariff. Environmental and energy taxes consist of energy tax, CO_2 tax, SO_2 tax, NO_x tax, and electricity tax. The taxes are levied on intermediate and final use of energy goods. For the composite energy good, "other petroleum fuels", the tax is based on each sector's use of the different fuels included in this composite.[18]

The emissions of CO_2, SO_2 and NO_x depend on each sector's use of each type of fossil fuel, i.e. each sector has a sector-specific emission factor for each type of fuel used. CO_2 emissions from one unit of a non-composite fuel type are equal in all utilization. However, for the composite fuel types used in the model, CO_2 emissions differ between users due to the differences in fuel composition. The emissions of SO_2 and NO_x from one unit of fuel are user-specific. Emissions originating from industrial processes are modeled as proportional to each sector's output level. The nitrogen (N) discharges are also included as a function of the output levels. Emissions from the use of other fuels not explicitly modeled, such as biofuels, are assumed to be constant at the benchmark level in all simulations.[19]

In addition to the standard Arrow-Debreu constraints, the model includes auxiliary constraints on the aggregate levels of emissions of the different pollutants. When aggregate emission of a pollutant exceeds the exogenously specified target, it results in an endogenous increase in the tax on the energy input. This tax increases proportionally on all polluting inputs and sectors simultaneously. There are also sector-specific employment constraints that endogenously scale up a subsidy on labor use to fulfill an exogenously specified employment target level. In addition, the model includes an equal yield constraint, accommodating the exogenous government budget constraint through the scaling of an exogenously chosen replacement tax or through lump sum transfers.

3.3 Benefits from emission reductions

Needless to say, to investigate whether a certain level of emission reduction can be economically justified, the benefit from these reductions must be quantified. The benefit calculation from an increased tax on CO_2 emissions should not only focus on gains from reduction in these emissions since there are also secondary benefits, such as reduction of local nitrogen oxide emission and sulfur emission, reduced traffic congestion etc. In this model, the benefits from reduced pollution levels enter the representative agent's utility function separable from the consumption of goods, services and leisure. This is clearly a strong assumption when environmental externalities most likely have effects on the consumer's

[18] The benchmark energy and environmental tax system is described in Appendix 1.

[19] See Appendix 2 for a formal description of emission calculations.

substitution between different goods (e.g. health services, tourism), and also have an impact on production due to, for example, effects on the resource stock (e.g. fisheries, agriculture, forestry). Another simplifying assumption is that these damages are linear with respect to emissions in the intervals considered. This assumption is due to limited availability of data on the nature of damage relationships. An additional shortcoming of this benefit analysis is that the model used here is static when most of the environmental damages are dynamic by nature. That is, the model is incapable of quantifying damages that are related to the accumulated stock of pollutants.

It should also be noted that the benefit estimates used below are associated with numerous uncertainties. Several external effects are excluded in the calculations due to lack of estimates for Sweden. Some of these effects are probably of non-negligible order, as suggested by non-Swedish studies, but transfering damage estimates geographically is, for most estimates, inappropriate.

The benefits from reduced carbon emissions are very uncertain. Cost estimates of damages from global warming are especially shaky due to the uncertain nature of the phenomenon, and the fact that a large portion of its anticipated effects will occur in a distant future. Several studies have estimated values for reduced CO_2 emissions, e.g. Nordhaus (1991, 1994), Fankhauser (1995), and Tol (1995). The results of these studies indicate a value per reduced kilo of CO_2 emission ranging from 0.03 up to 0.6 SEK.[20] Most of the values estimated in the literature are below 0.2 SEK, but with assumptions of more extreme damages in the future and low discount rates, the value of reduced emissions rises towards the higher level. In a study of the cost of road transport in Sweden, Leksell and Lövgren (1995) find that the environmental goals set up by the Swedish government in transport policies correspond to approximately 1 SEK per kilo of CO_2 emissions. Given these variations in estimated valuation, three different values for CO_2 emission reduction valuation are used in the simulations; 0.2, 0.4 and 0.6 SEK per kilo of CO_2 emitted.

The benefit from reduced sulfur dioxide emissions is based on a study by Andersson (1994), who estimates the cost of corrosion and degradation of buildings, infrastructure and vehicles due to sulfur deposition. Several (non-Swedish) studies of the damage from SO_2 emissions suggest that there are substantial costs due to negative health effects and, especially, mortality (see e.g. Burtraw et.al. (1997)). Unfortunately no (up to date) estimates of such effects are available for Sweden and, hence, this cost is not included in this study. The effect of sulfur emissions on forest growth has been highly debated in Sweden. Some studies indicate that sulfur deposition has a negative impact on forest growth, while other studies show zero or even a positive impact from these emissions.[21] Given the relatively large forest related industry in Sweden, a negative forest growth effect might have a significant influence on the Swedish economy. However, due to the ambiguity of damage costs in these studies and, more important, the incapability of the model to incorporate pollution stock effects, the effect on forest growth is not included in the environmental benefits calculations. Another, potentially important, negative effect from sulfur emission excluded in this paper is the acidifying effect on lakes, which is pollution stock related.

Several Swedish studies estimate the cost of increased deposition of nitrogen oxides and nitrogen. The model takes into account the cost from nitrogen discharges that arises due to effects on eutrophication, the ground water, sports fishery and health. The calculations of monetary estimates of non-health welfare impact are based on several different Swedish valuation studies.[22] The cost of reduced health due to NO_x emissions is mostly a problem in densely populated areas, where traffic is the major emitter. The valuation of health cost used in this study is based on cost estimates by Leksell and Lövgren (1995). Clearly, with the non-geographical characteristic of this model, it is impossible to quantify the amount of the NO_x emission reduction that will occur in densely populated areas. A simplifying assumption of proportional change of traffic work in all geographical areas is made in the calculations of health benefits from decreased emissions. The values used in the benefit calculations are summarized in Table 3.2.

Table 3.2 Welfare cost per kg emission SEK (1993)

Pollutant	Valuation
SO_2	11
NO_x	48.7^a, 0.7^b
N	20.4
CO_2	0.2, 0.4, 0.6

a) Emissions in densely populated areas from road transports.
b) Emissions in rural areas and from non-transport sources.

4. Policy simulations

In this section the model is used for assessing the effects of using two main CO_2 tax policy designs to attain emission reductions. The first policy considered uses a tax scheme with the tax exemptions present in the benchmark year, and the second uses sectorally uniform carbon

[20] All monetary magnitudes are in 1993 SEK.
[21] This also applies to the NO_x emissions discussed below.
[22] Unpublished calculations by I-M. Gren, The Beijer Institute of Ecological Economics.

taxes. The principal aim is to evaluate the effects on welfare, sectoral structure and emissions from the use of these different tax policies to attain a given CO_2 reduction goal. The effects of using the benchmark exemptions are also compared with the use of subsidies to avoid large employment effects in "sensitive" industries. Finally, the secondary benefits from CO_2 taxes are calculated, which enables (net) welfare cost quantification including environmental benefits. Similar to the labor subsidy scenario, the effects of the use of tax exemptions to increase secondary benefits are compared with a scenario where an additional tax on secondary emission is used to produce the same outcome with respect to both CO_2 and secondary emission.

In addition, the weak form of the double dividend claim is examined by comparing the welfare cost of a CO_2 tax reform where increased tax revenues are recycled by reducing a distortionary tax. The cost of this reform is compared with the outcome from a reform where the tax revenues are recycled in a lump-sum fashion, i.e. where the emissions are reduced with a non-revenue raising instrument. The strong form of the double dividend is examined by evaluating the cost of the former tax reform compared with status quo. The first CO_2 tax design, i.e. a tax system where the tax exemptions are maintained, is used in these double dividend evaluations.

The scenarios examined are as follows.

Tax exemption scenario: In this scenario, the CO_2 tax level ranges from zero, i.e. a complete removal of the benchmark carbon tax, up to a 200 percent increase of the benchmark tax. The benchmark tax exemptions are retained in this scenario, implying that, for all positive CO_2 tax rates, the exempted industries pay one fourth of the tax rates paid by other fossil fuel users.

Uniform tax scenario: In this scenario, the policymaker uses a CO_2 tax that is equal for all producers and consumers, i.e. the benchmark tax exemptions are removed. This implies that, for example, a doubling of the CO_2 tax benchmark level will correspond to an 8 times increase for the previously exempted industries.

Uniform tax with labor subsidies: This scenario is similar to the uniform tax scenario but the policymaker is assumed to have an employment constraint on previously exempted industries. If the aggregate labor input in these industries fall below the corresponding (tax exemption scenario) level, the government subsidizes labor use in these industries. The subsidy takes the form of an ad valorem labor subsidy.

Uniform CO_2 tax with secondary emission tax: This scenario is similar to the uniform tax scenario, but the policymaker is assumed to have a secondary emission constraint. If the emissions of NO_x and SO_2 exceed the corresponding tax exemption scenario level, a second fossil fuel tax is increased to maintain that level.

All scenarios with recycling of tax revenue uses payroll tax as a replacement tax, i.e. the payroll tax is adjusted to keep government consumption at the benchmark level. Furthermore, in this medium-term assessment, the domestically produced electricity is assumed to be inelastically supplied, reflecting the large share of (fixed) hydro and nuclear power production capacity. Finally, to facilitate the examination of sector-specific effects, a single emission target level (15 % reduction) is chosen in the discussion.

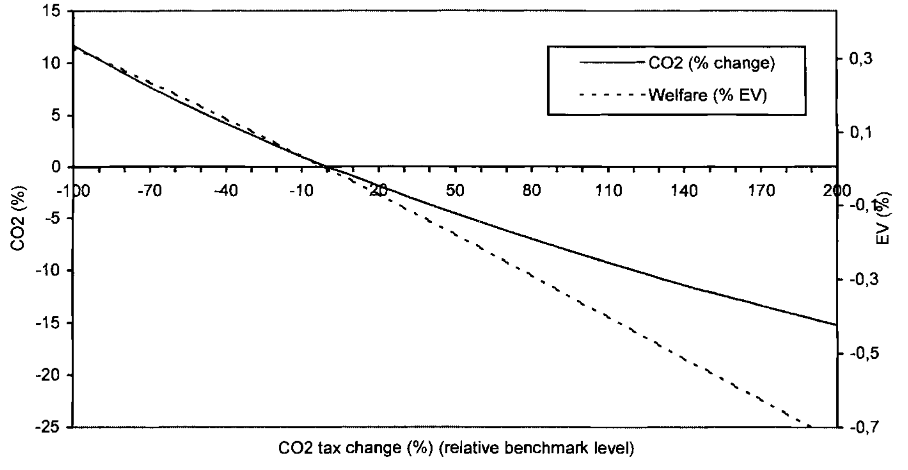
4.1 Simulation results

Welfare effects excluding environmental benefits

The Hicksian equivalent variation in income (EV) for the representative consumer is used as a measure of the welfare effect from different tax policies. If nothing else is indicated, this measure excludes any benefit the consumer might get from reduced pollution levels. The EV is shown as percentage of benchmark income and could be interpreted as the amount the representative consumer would be willing to pay for the policy to be implemented.

One significant finding is that all scenarios involving a revenue neutral carbon tax increase, will decrease aggregate welfare. That is, any policy resulting in an increase in the CO_2 tax on all sectors from the benchmark level will result in lower aggregate welfare. This is shown in Figures 4.1 and 4.2, where the change in welfare and the change in CO_2 emissions are graphed against the change in CO_2 tax. The welfare effect is measured on the right-hand vertical axes while the emission effect is measured on the left-hand axes. In Figure 4.1, the horizontal axis shows the carbon tax change from the benchmark tax level. The horizontal axis in Figure 4.2 shows the tax level relative the benchmark non-exempted sectors' tax levels, i.e. a value of 100 implies a double tax level for the non-exempted sectors and 8 times the benchmark tax level for previously exempted sectors.

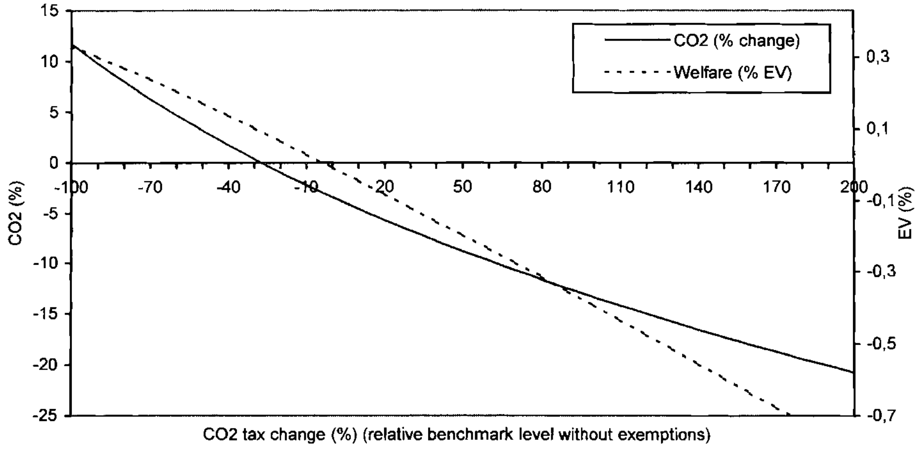
Figure 4.1 Effects on welfare and total emission: Tax exemption scenario



From Figure 4.1 it is clear that, if benchmark carbon taxes (with tax exemptions) are increased in a revenue neutral way, there will be a decrease in CO_2 emissions. Furthermore, the so-called revenue recycling effect that results when the payroll tax is reduced will not exceed the negative distortions caused by the tax increase, i.e. the tax interaction effect.[23] That is, there is no strong double dividend. Figure 4.2 illustrates a similar relationship; for every tax level higher than the benchmark level, the cost of the reform is positive, i.e. a uniform tax policy involving higher tax levels for previously non-exempted consumers will be costly. In addition, Figure 4.2 illustrates the magnitude of distortions caused by the benchmark use of CO_2 tax exemptions. By decreasing the taxes for non-exempted industries and consumers by approximately 27 percent and simultaneously removing the tax exemptions present at the benchmark, there is potential for a welfare gain without increasing in the aggregate CO_2 emission level. This also implies that there is a potential for a 4 percent decrease in emissions at no welfare cost.

[23] It is also clear from Figures 4.1 and 4.2 that the CO_2 tax is an inefficient tax for fiscal purposes at any positive level. In fact, a negative tax level, with an increase in payroll taxes to maintain revenue neutrality, will decrease the excess burden of the tax system further. This does not, however, imply that the total fossil fuel tax level should be negative. Several other taxes (such as the energy and the SO_2 tax) are levied at these goods at the benchmark.

Figure 4.2 Effects on welfare and total emission: Uniform tax scenario



The difference in total welfare cost between the revenue raising and non-revenue raising instrument use quantifies the second dividend, i.e. the revenue recycling effect, of CO_2 taxation.[24] For example, as shown in Table 4.1, with the tax exemptions, the cost savings from using revenue-raising taxes instead of non-revenue raising instruments (lump-sum recycling) is approximately 19 percent for a 15 percent emission reduction. This indicate, as expected, that the use of (revenue raising) taxes is superior to non-revenue raising instruments for any given level of emission reduction. The non-revenue raising policy reduces the overall economic activity and has an adverse effect on labor supply. This is because leisure becomes relatively more attractive as the price of goods consumption rises. In addition, the tax revenues from pre-existing taxes are reduced and the (budget-constrained) government must therefore increase the payroll tax (i.e. the chosen replacement tax), which further disturbs the labor-leisure choice. The net result is hence a decreased labor supply and higher payroll taxes. The (revenue-raising) tax policy also disturbs the labor-leisure consumption through increased price of consumption goods, but will, on the other hand, generate an increase in *net* tax revenues. This results in decreased payroll taxes, which offsets the negative effect on labor supply. The net result with this policy is, hence, increased labor supply.

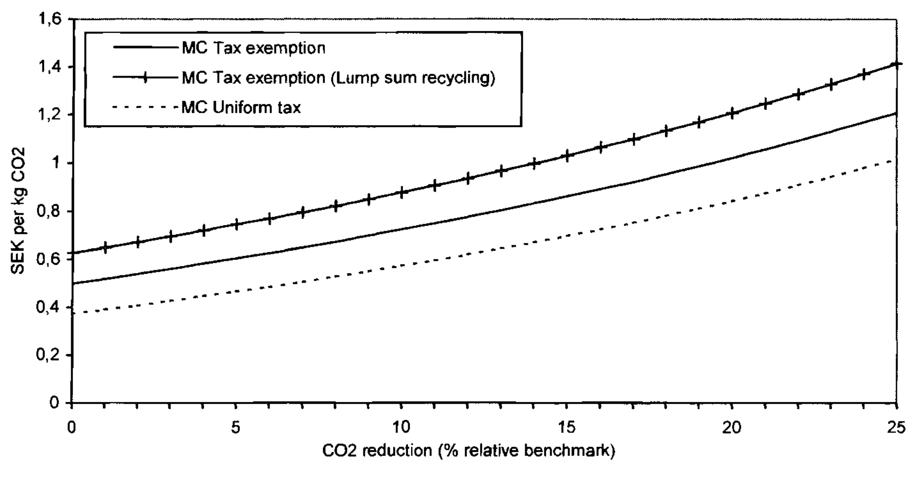
[24] Note that the values in the simulations does not give the full value of the revenue recycling effect as if the alternative were to remove all CO_2 taxes used at the benchmark. That is, the calculations do not include the revenue recycling of the benchmark CO_2 tax revenues, only the cost of using the different instruments starting from the benchmark situation with CO_2 taxes.

Table 4.1 Cost of CO_2 reduction (% EV excluding environmental benefits)

	Benchmark tax exemptions		Uniform tax	Uniform tax with labor subsidies
CO_2 Reduction (% from benchmark)	Lump sum recycling	Tax recycling	Tax recycling	Tax recycling
0	0.00	0.00	0.09	0.08
5	-0.25	-0.20	-0.06	-0.08
10	-0.54	-0.44	-0.25	-0.28
15	-0.89	-0.72	-0.47	-0.53
20	-1.29	-1.07	-0.75	-0.82
25	-1.77	-1.47	-1.09	-1.17

It is difficult to see the marginal cost effect of exemptions from Figures 4.1 and 4.2. The total welfare cost graphed in these figures clearly shows the *total* gain from uniform taxation when starting out from the *benchmark* tax system. Hence, large cost savings are possible for small emission reductions from the benchmark level due to pre-existing inefficiencies in the CO_2 tax. As shown in Table 4.1, the relative *average* cost advantage of uniform taxation is decreasing with increased CO_2 abatement. Figure 4.3 shows that limited substitution possibilities for fossil fuel inputs make larger emission reduction more costly on the margin. If the tax exemptions policy is used, this marginal cost increase will be more pronounced. That is, the marginal welfare cost disadvantage of the tax exemption policy increases with the emission reduction target. The uniform carbon tax implies a marginal cost ranging from 0.37 SEK per kg reduced carbon emission for the first kg, up to 1.02 SEK per kg at a 25 percent reduction level. The corresponding figures when the benchmark tax structure is maintained are 0.50 up to 1.21 SEK per kg.

Figure 4.3 Marginal welfare cost of CO2 emissions reductions



For a given valuation of emission reduction, the marginal welfare cost figures yield the optimal CO_2 reduction level, *excluding* secondary emission effects. For example, a valuation of 0.6 SEK per kg CO_2 corresponds to a 5 percent emission reduction level, if the exemptions are maintained and the tax revenue is recycled, and a 11 percent reduction with uniform taxation.

In addition, the marginal welfare cost saving from using a revenue-raising tax instrument is illustrated in Figure 4.3 by the difference between the marginal cost curves with and without lump sum recycling. The marginal welfare cost reduction that stems from the recycling of revenues, i.e. the "marginal second dividend", is 0.13 SEK per kg CO_2 at the benchmark. This implies that with a non-revenue-raising instrument, the valuation must exceed 0.6 SEK per kg CO_2 for any emission reductions to be beneficial (disregarding secondary emission effects).

Effects on domestic production and trade

To analyze the industry-specific effects on domestic production, exports and imports, a single emission reduction target of 15 percent has been chosen. The effects on the produced *goods* are shown in Table 4.2, and the effect on the producer *output* levels are shown in Table 4.3. Not surprisingly, there is a substantial decrease in the production and import of fossil fuel products that are heavily taxed. Due to the assumed constrained production level in the electricity sector, and an unchanged electricity tax, imports will increase substantially when energy users substitute from fossil fuel toward imported electricity.[25] Private consumers have a relatively higher fossil fuel-electricity substitution elasticity. Hence, when benchmark exemptions are maintained and their fuel use levied higher tax, the increase in imports is more pronounced, resulting in a CO_2 "leakage effect" if the imported electricity originates from fossil fuel intensive electricity production.

Another noteworthy observation is that relatively small changes in output levels are observed among several of the exempted sectors, regardless of the tax policy. The output reduction by steel and metal producers and in the chemical industry are, however, more sensitive to the choice of policy. The first observation can partly be explained by the fact that some of these sectors are not characterized by especially high CO_2 emissions per unit of labor input. That is, they are hit by the increased cost of fossil fuels but simultaneously benefit from lower labor cost. The independence of tax policy stems, at least partly, from the fact that

[25] The large increase of imports in percentage terms does not imply that a large quantity is imported after the tax reform. At the benchmark, imported electricity constituted approximately one percent of the domestic electricity use.

energy consumption in these sectors consists of sectorally uniform taxed gasoline and diesel to a fairly large extent. For a given CO_2 reduction target, these fuels will be taxed relatively lower in the uniform tax scenario and will therefore also benefit these sectors. This does, however, not apply to steel and metal producers, who, due to their large export share, also suffer from the international competitive environment and reduce their exports by a substantial amount. Furthermore, the steel sector has relatively limited substitution possibilities between energy and capital, resulting in limited changes in the sector's CO_2 per capital ratio, which indicates a potentially large adjustment cost. The model's "perfectly mobile capital assumption" will, however, not capture this effect. Finally, the uniform tax will, not surprisingly, benefit non-exempted users of diesel and gasoline such as the transport, fishing and agriculture sectors and the private consumer.

Table 4.2 Domestically produced goods and imports 15 % reduction of CO_2 emission (% change from benchmark)

Goods	Import		Domestic		Export	
	Tax exemption	Uniform tax	Tax exemption	Uniform tax	Tax exemption	Uniform tax
Gas	-21.4	-23.6	-21.2	-22.8	-21.0	-21.9
Agriculture	2.1	0.3	-1.4	-0.8	-4.7	-1.9
Forestry	-0.3	-1.9	-0.4	-0.5	-0.6	0.9
Fishing	9.4	4.7	-5.2	-3.0	-17.9	-10.1
Food and Textile	0.0	-0.1	-0.5	-0.6	-1.0	-1.0
Pulp and Paper	-0.4	-0.3	-0.3	-0.5	-0.2	-0.7
Chemical	0.0	0.4	-1.7	-3.9	-3.4	-7.9
Steel and Metal	1.7	2.7	-0.8	-5.6	-3.3	-13.3
Manufacturing	-0.5	-0.7	1.2	1.4	3.0	3.5
Electricity and Heat.	14.6	5.6	0.2	0.1	-12.4	-5.1
Water and Sewage	0.0	0.0	-0.5	-0.4	0.0	0.0
Construction	0.0	0.0	-0.2	-0.1	0.0	0.0
Transport	5.8	2.3	-3.4	-1.9	-11.7	-5.9
Trade and Services	-0.9	-2.0	-0.5	-0.4	0.0	1.3
Dwelling	0.0	0.0	-0.1	0.1	0.0	0.0
Coal and Coke	-15.6	-17.5	-16.0	-16.3	-16.3	-15.1
Heavy fuel oil	-18.4	-21.8	-17.7	-17.3	-17.0	-12.5
Other Mining	-10.7	-8.4	-13.6	-11.8	-16.3	-15.1
Other Petroleum	-12.6	-9.9	-14.9	-11.2	-17.0	-12.5

Table 4.3 Output and primary factor input. 15 % reduction of CO_2 emissions (% change from benchmark)

Sector	Output		Unskilled labor		Skilled labor		Capital	
	Tax exemptions	Uniform tax	Tax exemptions	Uniform tax	Tax exemptions	Uniform tax	Tax exemptions	Uniform tax
Petroleum[a]	-15.7	-12.0	-15.3	-11.8	-15.4	-11.9	-14.5	-11.0
Gas	-21.2	-22.8	-20.7	-22.4	-20.8	-22.5	-20.7	-22.3
Agriculture	-1.4	-0.8	0.1	0.1	0.0	0.0	1.1	0.8
Forestry	-0.4	-0.5	0.2	0.0	0.1	-0.1	0.4	0.1
Fishing	-8.6	-4.9	-5.4	-2.8	-5.6	-3.0	-3.5	-1.5
Mining[a]	-14.8	-13.4	-13.4	-11.5	-13.5	-11.5	-13.6	-11.4
Food and Textile[a]	-0.6	-0.6	-0.3	0.0	-0.4	-0.1	-0.1	0.3
Pulp and Paper[a]	-0.3	-0.5	0.2	0.2	0.1	0.1	0.4	0.8
Chemical[a]	-2.5	-5.6	-1.3	-3.7	-1.4	-3.7	-2.4	-5.3
Steel and Metal[a]	-1.6	-8.2	0.1	-4.6	0.0	-4.7	-3.2	-11.3
Manufacturing[a]	2.0	2.1	2.2	2.4	2.1	2.3	2.4	2.8
Electricity and Heat.	0.0	0.0	2.2	1.4	2.1	1.3	3.4	2.2
Water and Sewage	-0.5	-0.4	0.0	-0.1	-0.1	-0.2	0.3	0.2
Construction	-0.2	-0.1	0.4	0.2	0.3	0.1	1.4	1.0
Transport	-5.1	-2.7	-2.1	-0.8	-2.2	-0.9	-6.7	-3.7
Trade and Services	-0.4	-0.2	0.0	0.0	-0.2	-0.1	0.3	0.3
Dwelling	-0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.3

[a] Sectors with reduced tax rates in the benchmark year

Effects on labor demand and supply

The effect of a revenue neutral tax reform on employment is ambiguous. It is highly dependent on if the incidence of the environmental tax falls on workers, and how they benefit from the recycled revenue. When the revenue is recycled through lower taxes on labor, positive effects on employment could be expected. However, it is well known that taxes on consumption goods are implicitly a tax on labor. That is, if consumption taxes are increased, the excess burden will primarily fall on labor. If exemptions are maintained, the CO_2 tax falls, to a large extent, on gasoline consumed by the private consumer. Therefore, the labor-leisure choice could be relatively more distorted from the use of tax exemptions compared with the use of a uniform tax.

The model uses a simple description of the labor market. Unemployment is voluntary, i.e. consumers either supply their labor or consume it as leisure, and the labor market always clears. The assumption regarding the substitution elasticity between goods and leisure consumption is obviously important in this setting, and is therefore evaluated in the sensitivity analysis.

The aggregate effect of the tax reform on total labor supply is small but positive. The total effect is less than a 0.25 percent change of benchmark employment in all scenarios. This small effect could partly be explained by the relative size of the tax bases. For example, if the benchmark exemptions are maintained, a 15 percent emission reduction requires nearly a 200 percent increase in the benchmark CO_2 taxes (see Figure 4.1). As Table 4.4 shows, when revenues are recycled in a revenue neutral way, the payroll tax reduction will be about 8 percent, i.e. a reduction of approximately 3 percentage points.

Table 4.4 Effects on aggregate employment and payroll tax

	Tax exemptions		Uniform tax		Uniform tax with labor subsidies[a]	
CO_2 Reduction (% from benchmark)	Employment (% change)	Payroll tax (% change)	Employment (% change)	Payroll tax (% change)	Employment (% change)	Payroll tax (% change)
0	0.00	0.00	0.00	0.4	0.00	0.7
5	0.04	-2.8	0.04	-2.3	0.04	-1.9
10	0.08	-5.5	0.08	-5.1	0.08	-4.3
15	0.12	-8.2	0.13	-7.8	0.13	-6.8
20	0.17	-10.6	0.18	-10.5	0.17	-9.2
25	0.21	-12.9	0.22	-13.1	0.22	-11.5

[a]) Labor subsidies on the previously exempted sectors.

For a given payroll tax reduction, the aggregate effects do not seem to depend on if the tax, to a large extent falls on gasoline, or if it is more uniform on the different fossil fuels. Hence, the positive effect of uniform taxes discussed above fails to materialize in the simulations.[26]

The sector-specific effects on labor and capital use are shown in Table 4.3. Even though the aggregate effects on employment are small, the sector-specific impact could be substantial. The negative effects on employment in, for example, the steel and metal sector due to the use of uniform taxes can be used to justify carbon tax exemptions on these sectors. However, if other instruments such as sector-specific labor subsidies are available, the negative effects on employment can be counteracted more efficiently. If the policymaker wishes to save jobs in the exempted sectors that are threatened by a change to a uniform tax policy, a labor subsidy on these sectors is a more effective way of accomplishing this. A subsidy of less than 3 percent of the net labor cost on the affected sectors, will keep employment above the corresponding tax exemption level in all scenarios, but will also reduce the welfare gain from changing to uniform taxation (see Table 4.1). This reduction in welfare gain should, however, be compared with the reduced adjustment cost the labor subsidies bring about, which are not quantified by the model. An additional effect of labor subsidies is that they distort the labor market and reduce the potential for lower payroll taxes and, hence, have an adverse effect on labor supply to the non-subsidized sectors. The aggregate employment effect is, however,

[26] This result will, as the sensitivity analysis indicates, not necessarily hold if the labor supply elasticity is high.

modest due to the relatively small share of aggregate employment used by the subsidized sectors.

Effects on NO_x and SO_2 emissions and net cost

A carbon tax increase has effects on the emission levels of other pollutants such as SO_2 and NO_x. The emission coefficients for these pollutants are sector-specific, i.e. the aggregate emission of these pollutants is not proportional to the aggregate use of different fossil fuels in the economy. Therefore, changes in industrial structure will have effects on emission levels, even if the aggregate fossil fuel consumption remains constant.

Table 4.5 shows that, if benchmark tax exemptions are maintained, a decrease in CO_2 emissions will imply a decrease in both sulfur dioxide and nitrogen oxides emissions. The NO_x emission reduction will follow the CO_2 reduction very closely. However, if the uniform tax is used, both NO_x and SO_2 emissions will be relatively higher for any given CO_2 reduction level. An increase in these emissions is possible for low CO_2 target levels with a uniform tax. This effect is especially noteworthy in the NO_x case where, for example, the emission reduction is almost 40 percent larger if exemptions are maintained for a 15 percent CO_2 reduction.

Table 4.5 SO_2 and NO_x emissions (% reduction from benchmark level)

	Tax exemptions		Uniform tax	
CO_2 Reduction	SO_2 Reduction	NO_x Reduction	SO_2 Reduction	NO_x Reduction
0	0.0	0.0	-0.2	-1.8
5	3.1	4.5	2.8	2.0
10	6.3	9.0	6.0	6.0
15	9.5	13.8	9.2	10.1
20	12.7	18.6	12.4	14.5
25	16.0	23.5	15.8	19.1

The effect on NO_x emission can, to a large extent, be explained by the relatively lower tax levels levied on the fuels used for road transport. With a large part of the emissions originating from transportation, a high tax on this particular use of fossil fuel is likely to be more efficient in reducing NO_x emissions. The simulations indicate, however, that the average welfare cost per unit of reduced NO_x emission is nearly equal between the two different policy scenarios.

Based on the "secondary benefit" observation, it could be argued that the (net) cost of exemptions is lower than it appears, and that the exemptions therefore should be maintained. This argument can clearly be examined using a net benefit analysis, i.e. by including the value of secondary emission reductions in the simulations. This is done in the last part of this section. However, this could also assessed by studying the cost of *avoiding* the secondary emissions effect by a using second tax instrument. In Table 4.6, the costs of both these policies are shown, illustrating the cost saving from using a secondary instrument, a NO_X tax, to keep the secondary emissions (approximately) equal.[27] Clearly, the NO_X tax instrument is more efficient in correcting the secondary effects of the uniform tax than the use of tax exemptions. The welfare gain from using uniform taxation is, however, reduced by approximately 40 percent when the secondary emission constraint is introduced.

Table 4.6 Cost of emission reduction using CO_2 tax with exemption vs. uniform CO_2 tax and NO_X tax (% EV excluding environmental benefits[a])

CO_2 Reduction (% from benchmark)	CO_2 tax with exemptions	Uniform CO_2 tax with NO_X tax
0	0.00	0.05
5	-0.20	-0.11
10	-0.44	-0.31
15	-0.73	-0.57
20	-1.07	-0.86
25	-1.47	-1.21

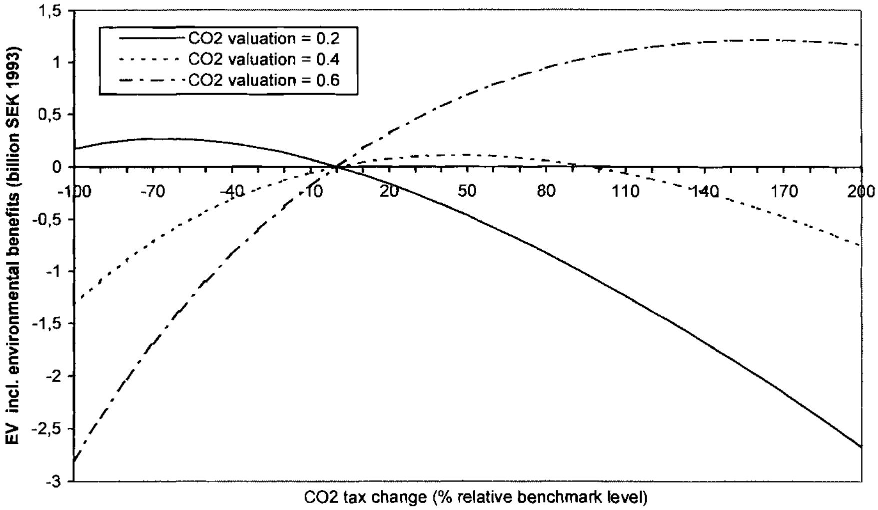
[a] Environmental benefits will, however, be approximately equal in the two scenarios.

The remainder of this section will examine the net cost of the CO_2 tax reform. From the sector-specific emission figures, it is possible to calculate the net benefits, i.e. the benefits including the valuation of the environmental gain, in a separable way by using the valuation figures presented in section 3.3. Figures 4.4 and 4.5 illustrate the net effects in the two main scenarios, with tax exemptions and uniform taxation, respectively. The benefits are calculated with different assumptions of the valuation of CO_2 emission reduction. The simulation results indicate that, given the benchmark tax exemptions, the benchmark CO_2 taxation cannot be improved if the valuation is below 0.32 SEK per kilo CO_2 reduction.[28] A lower valuation would imply that a lower tax rate improves welfare. As Figure 4.4 shows, if the valuation is

[27] In the simulations, the NO_x tax is a fuel-specific tax, based on the *average* emission factor for each fuel type. This NO_x tax also affects the SO_2 emission, so that these emissions approximately equal the corresponding exemption scenario emission level.

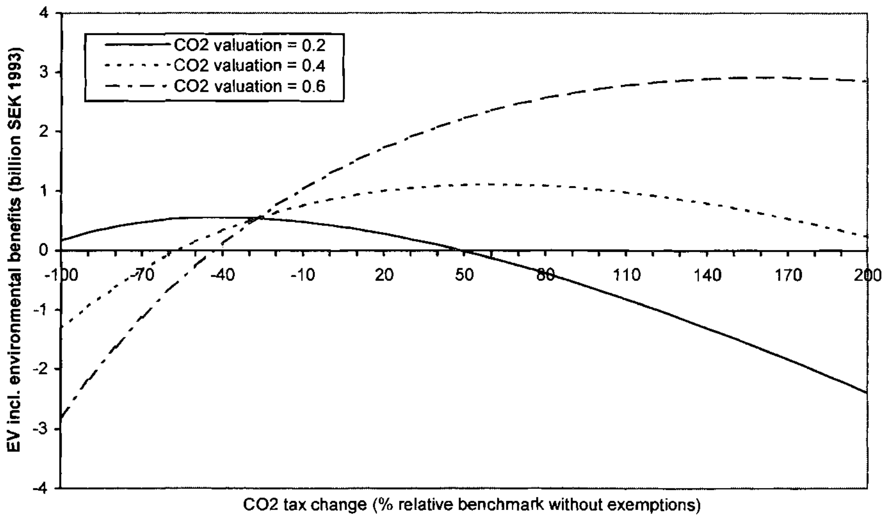
[28] Note that this value is lower than the corresponding value from Figure 4.3, 0.50 SEK. The latter value excludes the secondary benefits, and the difference between them is hence the marginal secondary benefits of CO_2 emission reduction.

Figure 4.4 Effects on welfare including environmental benefits. Tax exemption scenario.



0.2, then any (non-negative) tax rate lower than the benchmark rate will improve welfare, and the maximum will occur at a tax rate 65 percent lower than the benchmark rate. With a valuation of 0.4, a tax rate increase not exceeding 96 percent of the benchmark level improves welfare, and a maximum is reached at approximately 50 percent increase.

Figure 4.5 Effects on welfare including environmental benefits. No tax exemption scenario



In the scenario with uniform tax, greater welfare improvements are possible. As could be seen in Figure 4.5, with a valuation of 0.2 SEK per kilo of CO_2 reduction, net welfare maximization would imply a uniform tax rate of 60 percent of the non-exempted benchmark tax rate. That is, a 40 percent *lower* tax rate for the non-exempted sectors, and a 120 percent *higher* tax rate for the exempted sectors. This tax change would result in a 3 percent *increase* in CO_2 emissions and a net benefit of 560 million SEK. A valuation of 0.4 would imply a welfare maximizing tax rate 60 percent higher than the benchmark, non-exempted rate, resulting in an 11 percent CO_2 reduction. Finally, the simulations indicate that, with a uniform taxation, valuation has to exceed 0.24 SEK per kg CO_2 to justify any emission reductions from the benchmark level.[29]

The CO_2 valuation values used here are all on the high side of the estimates found in the literature. As noted in section 3.3, most estimates are below 0.2, which implies that an increase in CO_2 emissions resulting from lower CO_2 taxes increases net welfare. However, it should be noted that the valuation figures used for secondary emissions might be considered to be on the low side. Needless to say, all environmental benefit figures presented here should be interpreted with caution due to the high uncertainty associated with the estimates and the simplified way in which the emission-damage relationships are modeled.

5. Sensitivity analysis

A general equilibrium model such as the one used in this study could be criticized on several grounds, such as the functional forms used and the values of the exogenous parameters. It is particularly important to examine how robust the results are to the chosen elasticity values. To assess this, a number of sensitivity analyses of these values are carried out. First, an unconditional, systematic sensitivity analysis is employed as suggested in Harrison and Vinod (1992). Second, the sensitivity with respect to trade elasticity values, and the labor supply elasticities are examined. Finally, the effect of non-mobile sector-specific capital is also assessed.

In the first analysis, all elasticity values used in the model are assigned relatively large uniform distributions around the point estimates used in the analysis. The model is then solved repeatedly for a counter-factual scenario with elasticity values perturbed from the values used in the study. All elasticity perturbations are simultaneous and independent and each solution is given equal weight. The procedure is repeated until the sample size for each

[29] Note that this value is lower than the corresponding marginal cost value from figure 4.3, 0.37 SEK. The difference between these values is the marginal "secondary benefit" from CO_2 emission reduction with uniform taxes. That is, the marginal secondary benefits are 0.13 with uniform taxation, and (from the previous footnote) 0.18 with tax exemptions, which indicate that the removal of exemptions has an adverse effect on secondary emissions.

of the endogenous variables is 2000. The results are presented below with the mean and standard deviation generated for two key variables, welfare and the CO_2 tax level, in two main counterfactual scenarios; a 15 percent CO_2 emission reduction with or without benchmark tax exemptions. The results are shown in Table 5.1 and do not indicate that the model results are particularly sensitive to these elasticity perturbations. The mean is close to the values found when using the point estimates, and the standard deviation is not uncomfortably high.

Table 5.1 Sensitivity analysis of welfare and CO_2 tax impacts. Scenarios with 15 percent CO_2 emission reduction (sample size 2000)

	Welfare (% EV)			Carbon tax level (% Change from benchmark non-exempt level)		
Scenario	Point estimate	Mean	Std. Dev.	Point estimate	Mean	Std. Dev.
Tax exemptions	-0.72	-0.73	0.073	197.4	196.3	0.25
Uniform tax	-0.47	-0.48	0.059	120.2	119.5	0.16

The assumed values of trade elasticities could potentially have a large impact on the results. Due to lack of estimates for Swedish trade elasticities, a highly simplifying assumption of uniform Armington elasticities of 4.0 is used. To see the effect of this assumption, simulations with one fourth, half and double benchmark trade elasticities are carried out. With higher elasticity values, the effect on imports and, hence, emissions "leakage" could be expected to rise. This might be especially noticeable if the exemptions were to be removed. To investigate this, simulations with substantially higher (4 times) Armington elasticities on the exempted sectors and benchmark elasticities on the other sectors are carried out. The results from these simulations are shown in Table 5.2.

Table 5.2 Sensitivity analysis with respect to trade elasticities. Scenarios with 15 percent CO_2 emission reduction

	Welfare (% EV)			
Scenario	Base case values	One fourth trade elast.	Double trade elast.	Four times trade elast. on exempted industries
Tax exemptions	-0.72	-0.76	-0.67	-0.67
Uniform tax	-0.47, -0.53 [a]	-0.56	-0.39	-0.36, -0.46 [a]

[a] Labor subsidies on previously exempted sectors.

These results indicate that there is no substantial effect on aggregate welfare from changes in trade elasticities. For a given emission target, higher trade elasticities yield lower welfare cost, because it becomes easier to substitute toward imported goods when taxes on domestic production are increased. If the production by exempted industries is easier to substitute for imports, the cost of the tax reform using a uniform tax becomes lower. However, if the policymaker wants to avoid large changes in the level of employment in the exempted sectors, the difference between the benchmark elasticity specification and the high trade elasticity specification becomes smaller. That is, when production in this sector "moves abroad", the negative effect on employment is large, and will thus require large, costly labor subsidies.

The assumed labor supply elasticity value is clearly an important parameter when examining tax reforms involving changes in the tax on labor and/or large price changes in consumer goods. In the model economy, the consumer's labor-leisure choice depends on the relative price of leisure and consumption. With a positive labor supply elasticity, a ceteris paribus decrease in the labor tax will make consumption less expensive in terms of forgone leisure time and will increase the labor supply. However, if the price of consumption rises simultaneously, due to e.g. an increase in carbon tax, the total effect is ambiguous.

The results of increased labor supply elasticity are shown in Table 5.3 and indicate that the main conclusion is robust to the elasticity assumption. The use of tax exemptions substantially increases the cost of reaching the emission target. It is, however, interesting to note that if tax exemptions are maintained, the welfare cost will increase with the labor supply elasticity, while it remains unchanged in the uniform tax scenario. That is, the relative advantage of uniform taxation increases with the labor supply elasticity. One likely cause for this result is that, for a given emission reduction level, a higher tax on gasoline and diesel is necessary if exemptions are maintained, implying a relatively high direct effect on private consumption. This increases the relative price of consumption, i.e. increases the implicit tax on labor, and works against the positive effect on labor supply that arises when tax revenues are recycled through the labor tax. In fact, with a labor supply elasticity of 0.6, the effect of the tax reform with maintained exemptions is an aggregate labor supply *decrease* although payroll taxes are decreased.[30]

Table 5.3 Sensitivity analysis with respect to labor supply elasticities. Welfare effects (%EV) in the scenario with 15 percent CO_2 emission reduction.

Uncompensated labor supply elasticity	Base case (0.12)	0.3	0.6
Tax exemptions	-0.72	-0.76	-0.81
Uniform tax	-0.47	-0.47	-0.47

[30] The labor supply in this scenario decreases with 0.15 percent. The corresponding effect with a uniform carbon tax is a 0.11 percent increase.

The assumption of perfectly mobile capital between production sectors might be plausible in the medium or long run. However, some sectors could be assumed to have non-mobile capital also in the long run. This is probably true for sectors using natural resources, such as the forest, agriculture, fishing and mining industries. To investigate the effects of this assumption, simulations with sector-specific capital are carried out.[31] The results from a 15 percent CO_2 reduction target, with and without exemptions, are presented in Table 5.4 below. In the simulations, the sector-specific part of capital constitutes 80 percent of total capital input in the forest, fishing and agriculture sectors, and 50 percent in the mining sector.

Table 5.4 Sensitivity analysis with respect to domestic capital mobility assumption.[a] Scenario with 15 percent CO_2 emission reduction

Scenario[b]	Welfare (% EV)		Carbon tax (% change)	
	Base case	Lower mobility	Base case	Lower mobility
Tax exemptions	-0.72	-0.73	197.4	199.1
Uniform tax	-0.47	-0.49	120.2	121.2

[a] Sector-specific capital: 80 percent in forest, fishing and agriculture sector, and 50 percent in the mining sector.

The introduction of sector-specific capital in the model changes the effect on the sectors using natural resources but does not change the aggregate results substantially. As shown in Table 5.4, with fixed capital in some sectors, the CO_2 tax must be increased slightly more than in the fully mobile case. Not surprisingly, less mobile factors result in a higher cost of a given CO_2 reduction. The impact on welfare cost is, however, modest in both scenarios.

6. Summary and conclusion

This study has assessed the costs and benefits of using CO_2 taxes as a policy instrument to reduce domestic CO_2 emissions. By using a static CGE model of the Swedish economy, four main results are obtained. First, the use of a revenue-raising CO_2 tax instead of a non-revenue-raising instrument will always be superior. By recycling the carbon tax revenue through reduced payroll taxes, the marginal welfare cost of CO_2 abatement can be reduced by more than 0.13 SEK per kg CO_2. Second, the total cost of the benchmark CO_2 tax system is significantly increased by the use of tax exemptions on "sensitive industries". Furthermore, the initial marginal welfare cost of emission reductions is decreased from 0.50 to 0.37 SEK per kg CO_2 if the benchmark system is replaced by a uniform tax. Third, adverse effect on employment resulting from uniform taxation cannot motivate the use of exemptions. These

[31] In these simulations the capital input in the production function is replaced by an aggregate capital CES nest with sector-specific capital and (domestically) fully mobile capital.

effects can be mitigated at a lower cost by using direct labor subsidies on the affected sectors. Finally, if the valuation of changes in secondary emissions (NO_x and SO_2) is included in the calculations, the marginal welfare cost of CO_2 reduction is reduced to 0.32 and 0.24 for the benchmark tax system and the uniform tax, respectively. This implies that, if the valuation of SO_2 and NO_x reduction is taken into consideration, the current carbon tax level can be justified if the valuation of CO_2 emission reductions exceeds 0.32 SEK per kilo.

The model used in this study does not take into account some potentially important effects from a tax reform. First, the model is static and, hence, unable to include effects on capital formation or pollution accumulation. Neither does it consider policy-induced effects on technological development. There is also a need to study the short-run adjustment costs that are likely to be substantial if, for example, the tax exemptions are removed on some sectors. The importance of the valuation of reduced CO_2 emissions indicates the need for estimating people's willingness to pay for emission abatement. Further research also needs to be carried out on environmental damage relationships to enable improved modeling of environmental benefits.

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Appendix 1

Benchmark data

The benchmark data set for the model represents Sweden in 1993. The basic social accounting matrix is based on input-output tables by Statistics Sweden (SCB) and The Swedish National Institute of Economic Research. The production and consumption of fossil fuel have been further disaggregated by using data published in SCB (1995). The emission data used in the model describes each sector's emission of CO_2, SO_2 and NO_x divided into the use of different fossil fuels and the emission from industrial combustion. The sector-specific emission coefficients are based on unpublished calculations by SCB. Table A1 provides an overview of the modeled sectors' economic activity and emission patterns in the benchmark year.

Table A1 Some benchmark economic and emission data

						Emissions[e]	
SNR Code[a]	Sector	Output[b]	Labor[c]	Capital[d]	CO_2	SO_2	NO_x
	Petroleum[f]	26.5	0.8	5.6	1739,0	5,8	3,9
1100	Agriculture	29.3	4.3	10.2	1377,0	0,6	19,0
1200	Forestry	19.6	4.1	10.7	424,0	0,1	13,8
1300	Fishing	1.0	0.1	0.5	157,0	0,1	4,7
2000	Mining[f]	9.8	2.4	1.0	441,0	2,6	4,6
31-3300, 3600	Food & Textile[f]	177.7	34.3	21.1	4660,0	12,0	15,8
3400	Pulp & Paper[f]	117.2	27.1	17.7	1972,0	17,6	16,0
3500 (Exl. 3531)	Chemical[f]	75.8	15.5	14.4	2025,0	3,9	4,3
3700	Steel & metal[f]	49.7	8.9	3.4	6374,0	8,8	6,6
3800, 3900	Manufacturing[f]	313.1	91.2	24.1	1005,0	0,7	2,6
4100	Electricity & heat.	54.6	7.2	29.6	8876,4	15,1	16,0
4300	Water & Sewage	10.4	0.8	5.9	20,0	0,0	1,0
5000	Construction	157.3	61.9	16.9	1466,0	0,5	5,9
7100	Transport	130.8	41.6	20.1	11892,0	22,1	119,6
6000, 7200, 8000 (Exl. 8310)	Trade & Services	589.0	237.4	116.3	3416,0	0,6	55,7
8310	Dwelling	276.0	18.0	196.9	717,0	1,1	2,1
4200	Gas	1.7	0.1	0.6	16,6	0	0
	Government				1994,0	1,0	3,0
	Private consumer				14749,0	6,0	102,0
Total					63321,0	98,6	396,6

Source: SCB (1996)
a) Sector code in Swedish National Accounts.
b) Excluding taxes and subsidies. (Billion SEK_{93})
c) Including social security payments. (Billion SEK_{93})
d) Capital consumption and net operating surplus. (Billion SEK_{93})
e) SO_2, NO_x and CO_2 emissions in 1000 ton. CO_2 emissions excluding emissions from biofuels.
f) Sectors with lower CO_2 tax rate.

Environmental and energy taxes

The Swedish environmental and energy tax levels have been changed several times in the years prior to 1993. However, the model is calibrated to the 1993 tax system that has a similar environmental and energy tax structure (and exemptions) as the tax system today. The 1993 taxes are shown in Table A2. The ad valorem tax rates used in the model are calculated using yearly average fossil fuel prices. Weighted average prices have been used in the cases where these prices differ between energy users. The benchmark energy prices used in the model are described in SPI (1994) and NUTEK (1997).

At the benchmark, the industry is levied full SO_2 tax, one fourth of the CO_2 tax, and zero energy tax, on all energy inputs except petrol and diesel for which they pay full tax.[32] The sectors with these lower tax rates are indicated in Table A1. However, there is a possibility for some sectors to receive a refund if certain pollution reducing actions are taken. At the benchmark, these actions result in some industrial sectors only pay approximately half the SO_2 tax rate.

Table A2 Benchmark environmental and energy taxes[a]

	Energy	CO_2	SO_2	Total
Gas oil (SEK/m^3)	540	920	0	1460
Heavy fuel oil (SEK/m^3)	540	920	108	1568
Petrol (SEK/liter)	3,14	0,77	0	3,91
Diesel (SEK/liter)	1,59[b]	0,96	0	2,55
Natural gas (SEK/1000 m^3)	175	680	0	855
Coal (SEK/ton)	230	800	150	1180
LPG (SEK/ton)	0	240	0	240

Source: NUTEK (1995), SPI (1994)
[a)] Taxes apply to non-industry consumers and are net of VAT. Tax on LPG is industry rate. There is no LPG consumption by non-industry at the benchmark.
[b)] Includes Diesel tax

Electricity is taxed as an output; therefore electricity production pays zero energy and CO_2 tax. They do, however, pay full SO_2 tax on their inputs.[33] The electricity tax is only levied on non-industry consumers at a net of VAT rate of 0.085 SEK per kWh.[34] There is no NO_x tax, but there is a refundable NO_x charge that only applies to heat and power plants. This charge is not explicitly included in the model. In the benchmark year, the total revenues from CO_2 and SO_2 taxation where 11315 and 217 million SEK, respectively.

[32] Special reductions for energy and CO_2 tax rates applied to 11 firms in the benchmark year. This resulted in a total reduction of 60 million SEK to these firms in 1993 (of which one firm received 54 million SEK). These special reductions are not explicitly included in the model.
[33] The electricity sector also includes (a relatively small) production of district heating that pay taxes on fossil fuel use. These taxes are modeled as reduced tax rates for fossil fuel inputs into this sector.
[34] A lower rate of 0.035 SEK per kWh excluding VAT applies to certain parts of northern Sweden. These lower rates are not explicitly modeled.

Elasticities

Elasticity values have to be assembled for all nesting levels in production and consumption. This is primarily done by searching the literature for econometrically estimated values, preferable sector-specific values. For some of the values, reliable econometric estimates are scarce, and the used values are therefore subject to a margin of error. In the sensitivity analysis (section 5), all elasticity values are simultaneously randomly perturbed around the point estimates shown in Table A3. In addition, the effects of the trade and labor supply elasticity assumptions are assessed separately.

Table A3 Key elasticities used in the model

Description	Value
Production	
Elasticity of substitution between non-energy intermediate inputs and the composite of primary factors and energy inputs	0.0
Elasticity of substitution between labor aggregate and a composite of energy goods and capital.	0.58-0.94[a]
Elasticity of substitution between unskilled and skilled labor	1.2
Elasticity of substitution between capital and energy goods.	0.17-0.98[b]
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6
Elasticity of transformation between heavy fuel oil and other fuels in the petroleum sector	4.0
Elasticity of transformation between coal and other mining outputs in the mining sector	4.0
Elasticity of transformation between goods for domestic market and goods for export market	4.0
Armington elasticity of substitution between imported and domestically produced goods	4.0
Private Consumption	
Labor supply elasticity	0.12
Elasticity of substitution between skilled and unskilled leisure	0.5
Elasticity of substitution between aggregate non-energy goods and a composite of energy goods	0.4
Elasticity of substitution between different non-energy goods	1.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	1.0
Armington elasticity of substitution between imported and domestically produced goods	4.0
Government consumption	
Elasticity of substitution between different non-energy goods and a composite of energy goods	0.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6

a) 0.58 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.62 in paper and pulp. 0.76 in food and textile. 0.85 in chemical. 0.87 in transport. 0.92 in steel and metal. 0.94 in mining.
b) 0.17 in steel and metal. 0.31 in transport. 0.49 in chemical. 0.75 in food and textile. 0.87 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.91 in paper and pulp. 0.98 in mining.

Possibly the most important elasticity values in the model are the values concerning substitution between labor and capital-energy aggregate, and between capital and energy. These values are based on sector-specific estimates by Kemfert and Welsch (1997). Due to lack of sector-specific estimates, the energy-energy elasticity values are uniform across sectors and assumed to be 0.6, which is in line with the "standard" values found in the literature.[35] Based on empirical evidence[36], the possibility to substitute between different fossil fuels and electricity among households is assumed to be larger than in the industry. The

[35] See Burniaux et al. (1992) for an overview.
[36] See Andersson (1993).

Armington trade elasticities used are, in lack of good econometric estimates, assumed to be 4.0 and equal for all sectors and consumers, which is comparable with values used by e.g. Harrison et al. (1997).

Appendix 2

Algebraic model description

This section provides an algebraic description of the technology, preferences, market clearance conditions and additional constraints. The model is formulated as a nonlinear system of inequalities using GAMS/MPSGE (Rutherford, 1999), and is solved using PATH (Dirkse and Ferris, 1995). The inequalities are derived from the Arrow-Debreu general equilibrium conditions: zero-profit for the constant-returns to scale producers, income balance for the representative consumer and the government, and market clearance for all goods and factors and balanced trade with the rest of the world.

Table A4 Variable description

Variables and Parameters	Description
j	Production sector index
f	Petroleum and mining sector index
i	Goods index
F	Primary factor index
g	Pollutant index
Y_j	Domestic production from sector j
Z_i	Domestic production of good i
D_i	Domestic sales of good i
X_i	Export of good i
M_i	Import aggregate of good i
A_i	Armington aggregate of good i
K	Input of primary factor capital
L_U	Input of primary factor unskilled labor
L_S	Input of primary factor skilled labor
E	Primary factor supply
T	Lump-sum transfers from government to consumers
B	Current account balance net capital inflows
I_i	Final demand good i for investment purposes
W	Welfare index for representative consumer
V	Environmental benefits
P_j	Purchasers price of Armington aggregate good i
P_F	Purchasers price of primary factor F
P_D	Price of domestic produced goods for the domestic market net of subsidies
P_X	Exogenous price of goods for the export market net of subsidies
p_M	Exogenous price of imported goods for the net of tariffs
t_v	Goods specific ad valorem value added tax, excluding tax multiplier
t_F	Factor specific ad valorem factor tax, excluding tax multiplier
t_g	Benchmark good and consumer specific ad valorem tax on pollutant g
t_{Energy}	Good and consumer specific ad valorem energy tax
$t_{Elec.}$	Consumer specific ad valorem electricity tax
τ_M	Import tariff
θ_t	Tax multiplier for tax t
S	Net subsidy on output from domestic producer
mc_j	Marginal cost of production in sector j

Table A4 (cont.)

Variables and Parameters	Description
σ	Elasticity of substitution
ε	Elasticity of transformation
$a, b, \alpha, \beta, \gamma, \delta, \xi$	Scaling and share parameters
e^g	Domestic emission level of pollutant g
Ψ	Domestic emissions from fuels not explicitly modeled

Producers

The domestic producers use primary factors and intermediate goods to produce their output with a constant elasticity of substitution (CES) technology. For all sectors $j \neq f$, i.e. not including the petroleum and mining sectors, output, Y_j, is produced according to

$$Y_j = \min\left[\frac{A_{1j}^{NE}}{a_{1j}}, \ldots, \frac{A_{nj}^{NE}}{a_{nj}}, \frac{VE_j}{a_{VEj}}\right], \tag{A.1}$$

where A_{ij}^{NE} is the input of non-energy intermediate good i into sector j. VE_j is a nested CES aggregate of value added and energy goods,

$$VE_j = \left[\gamma_{L_j} L_j^{(\sigma_{Lj}-1)/\sigma_{Lj}} + \gamma_{KE_j} KE_j^{(\sigma_{Lj}-1)/\sigma_{Lj}}\right]^{\sigma_{Lj}/(\sigma_{Lj}-1)},$$

where L_j is a CES labor aggregate of skilled and unskilled labor. KE_j is a nested CES aggregate in which the producers choose between capital and composite energy input. At the final level, a constant elasticity then describes the substitution between the five different energy good types.

The petroleum and mining sectors have a Leontief input structure,

$$\hat{Y}_f = \min\left[\frac{A_{1f}^{NE}}{a_{1f}}, \ldots, \frac{A_{nf}^{NE}}{a_{nf}}, \frac{VE_f}{a_{VEf}}\right], \tag{A.2}$$

but differ from the other sectors in that they each produce two types of output using a constant elasticity of transformation frontier,

$$\hat{Y}_f = \left[\alpha_{f^1} Y_{f^1}^{(\varepsilon_f-1)/\varepsilon_f} + \alpha_{f^2} Y_{f^2}^{(\varepsilon_f-1)/\varepsilon_f}\right]^{\varepsilon_f/(\varepsilon_f-1)}, \tag{A.3}$$

where f^1 and f^2 index the two different outputs.

The industry output is transformed into consumption and intermediate goods using a fixed coefficient technology, that is, for all goods i,

$$Z_i = \min\left[\frac{Y_{1i}}{b_{1i}},\ldots,\frac{Y_{ki}}{b_{ki}}\right]. \tag{A.4}$$

Exports and imports are modeled using the Armington assumption. This means that domestic products produced for the domestic market are treated as qualitatively different from products exported to abroad or imported from abroad. On the export side, Z_i is, consequently, split into goods destined for the domestic market, D_i, and goods destined for the export market, X_i, according to a constant elasticity of transformation function

$$Z_i = \left[\alpha_{D_i} D_i^{(\varepsilon_i-1)/\varepsilon_i} + \alpha_{X_i} X_i^{(\varepsilon_i-1)/\varepsilon_i}\right]^{\varepsilon_i/(\varepsilon_i-1)}. \tag{A.5}$$

On the import side, the aggregation of domestic and import goods is described by a CES function:

$$A_i = \left[\beta_{D_i} D_i^{(\sigma_i-1)/\sigma_i} + \beta_{M_i} M_i^{(\sigma_i-1)/\sigma_i}\right]^{\sigma_i/(\sigma_i-1)}. \tag{A.6}$$

Import supplies and export demands are infinitely elastic, i.e. the world market prices (p_X and p_M) are given, and the small open economy does not experience any change in terms of trade. The current account, B, is balanced, including the exogenously specified capital inflows,

$$B + \sum_i p_X^i X_i = \sum_i p_M^i M_i, \tag{A.7}$$

where import and export prices are exogenous parameters. This trade balance constraint has an associated variable that could be interpreted as the "real exchange rate", which adjusts to assure that the equality is satisfied.

Government and private consumers

The representative private consumer's utility function is a three level CES function with a separable environmental benefit part $V(\mathbf{e})$ where $\mathbf{e}$ is a vector of emission levels from each sector. $V(e)$ is a linear function of emissions of each pollutant and each sector. At the top level, the consumer allocates its time endowment between work and aggregate leisure,

$$W = \left[\delta_H PC^{(\sigma_{CL}-1)/\sigma_{CL}} + \delta_L L_C^{(\sigma_{CL}-1)/\sigma_{CL}}\right]^{\sigma_{CL}/(\sigma_{CL}-1)} + V(\mathbf{e}). \tag{A.8}$$

The leisure is then chosen to be of "skilled" or "unskilled" type

$$L_C = \left[\delta_{L_U} L_{UC}^{(\sigma_{LL}-1)/\sigma_{LL}} + \delta_{L_S} L_{SC}^{(\sigma_{LL}-1)/\sigma_{LL}}\right]^{\delta_{LL}/(\sigma_{LL}-1)}.$$

The consumer then decides how much to spend on energy goods and non-energy goods, described by

$$PC = \left[\delta_H H^{(\sigma_{CN}-1)/\sigma_{CN}} + \delta_C N_C^{(\sigma_{CN}-1)/\sigma_{CN}}\right]^{\sigma_{CN}/(\sigma_{CN}-1)}.$$

The spending is, in turn, divided into different non-energy goods ($i \in Q$),

$$H = \left[\sum_{i \in Q} \delta_i A_{iC}^{(\sigma_{CC}-1)/\sigma_{CC}}\right]^{\sigma_{CC}/(\sigma_{CC}-1)},$$

and different energy goods,

$$N_C = \left[\sum_{i \notin Q} \delta_i A_{iC}^{(\sigma_{NN}-1)/\sigma_{NN}}\right]^{\sigma_{NN}/(\sigma_{NN}-1)}.$$

Consumers maximize W taking market prices and **e** as given subject to its budget constraint,

$$\sum_i p_{iC} A_{iC} \leq \sum_j \sum_F p_j^F \left(1 - \tau_j^F\right) E_{Fj} + \theta_T T + B - I, \tag{A.9}$$

i.e., the value of consumption is less than or equal to the net income from primary factors plus lump sum transfers from the government, $\theta_T T$, plus the exogenously given foreign exchange balance, B, less investment, I. Labor supply, E_L, equals labor endowment net leisure consumption.

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 incomes. The government objective function has a two level nesting structure with a Leontief top nest with fixed proportions of different non-energy goods and an energy composite, and a second level with constant elasticity of substitution between energy goods reflecting a possibility to substitute between these inputs. That is,

$$GOVT = \min\left[\frac{A_{1G}}{\alpha_{1G}}, \ldots, \frac{A_{nG}}{\alpha_{nG}}, \frac{N_G}{\alpha_{EG}}\right], \tag{A.10}$$

where the energy nest is

$$N_G = \left[\sum_{i \notin Q} \xi_{iG} A_{iG}^{(\sigma_{NG}-1)/\sigma_{NG}} \right]^{\sigma_{NG}/(\sigma_{NG}-1)}.$$

Government total demand is held constant at the benchmark level in all simulations. Its budget constraint is accommodated through endogenous scaling of an exogenously determined tax. The government budget constraint is described by

$$\begin{aligned} \sum_i p_{iG} A_{iG} \le \sum_j \sum_F \tau_j^F p_j^F E_{Fj} + \sum_j \tau_{ij}^A p_{ij}^A A_{ij} + \sum_r \tau_{ir}^A p_{ir}^A A_{ir} \\ + \sum_i \tau_i^M p_i^M M_i - \sum_i s_i \left(p_i^D D_i + p_i^X X_i \right) - \theta_T T \end{aligned} \quad \text{(A.11)}$$

In all simulations, both the government and private investments are exogenous and kept at the benchmark level.

Taxes, tariffs and transfers

τ_F represents the factor taxes levied on primary factor F. These sector-specific factor taxes include labor and capital tax, as well as the sector's share of the value added tax levied on produced goods,

$$\tau_j^F = \theta_{Fj} t_j^F + \theta_v t_j^v, \quad \text{(A.12)}$$

where the labor taxes, $t_j^{L_U}$ and $t_j^{L_S}$, for each type of labor, consist of payroll and income tax. θ is the tax multiplier that endogenously scales the (exogenously) chosen replacement tax to accommodate the government budget constraint. The multiplier θ_T in (A.11) analogously, scales the transfers if lump-sum taxes are used to fulfill the budget constraint.

The ad valorem tax on intermediate and final use of energy goods is

$$\tau_{ij}^A = \theta_{CO_2} t_{ij}^{CO_2} + \theta_{SO_2} t_{ij}^{SO_2} + \theta_{NO_X} t_{ij}^{NO_X} + t_{ij}^{Energy} + t_{ij}^{Elec.}, \quad \text{(A.13)}$$

where the θ:s are endogenous tax multipliers for each of the three pollutants, associated with the environmental constraints discussed below. Finally, s_i is the net subsidy on domestically produced goods, and τ^M is the import tariff levied on non-domestically produced goods.

Price-cost balance

All production activities use constant return 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 j, mc_j, is defined by

$$mc_j Y_j = \sum_i \left(1+\tau_{ij}^A\right) p_i^A A_{ij} + \sum_F \left(1+\tau_j^F\right) p_j^F E_{Fj} \,. \tag{A.14}$$

The zero profit condition for production of good i then becomes

$$\left(1+s_i\right)\left(p_i^D D_i + p_i^X X_i\right) = \sum_j mc_j Y_{ji} \,. \tag{A.15}$$

In the Armington aggregation activity, the zero profit condition implies that the gross value of Armington output equals the cost of domestic inputs plus the value of imports gross of import tariff,

$$p_i^A A_i = p_i^D D_i + \left(1+\tau_i^M\right) p_i^M M_i \,. \tag{A.16}$$

Supply-Demand balance

The market clearance condition requires that the supply from the Armington aggregation function equal investment, and intermediate and final demand.

$$A_i = \sum_j A_{ij} + A_{iC} + A_{iG} + I_i \,. \tag{A.17}$$

The factor market prices are fully flexible, i.e. the factor market always clears and equalizes factor demand with factor endowment,

$$\sum_j E_{Fj} + E_{FC} = E_F \,. \tag{A.18}$$

Environmental constraints

The emission tax multipliers in equation (A.15) have an associated constraint that specifies the aggregate target emission level of pollutant g,

$$e^g \le \bar{e}^g \tag{A.19}$$

where $\bar{e}^g$ is the exogenously specified target level for pollutant g. The total domestic emission level, e^g, is endogenously calculated as

$$e^g = \sum_i \mu_{iG}^g A_{iG} + \mu_{iC}^g A_{iC} + \sum_j \mu_{ij}^g A_{ij} + \eta_j^g Y_j + \Psi_j^g \,, \tag{A.20}$$

where μ_{ij}, μ_{iG} and μ_{iC} are the consumer and sector-specific emission coefficients for input i. μ_i is non-zero only for different fossil fuels. The emissions from industrial processes are assumed to be proportional to a sector's output level with coefficient η_j. Ψ_j is sector j:s emissions from consumption of "other fuels", e.g. biofuels, not explicitly modeled in the model. These emissions are assumed to be constant at the benchmark level in all simulations. The multiplier θ_g in equation (A.13) is endogenously scaled up or down to satisfy its associated constraint (A.19). The emissions originating from foreign countries are exogenously set to the benchmark level.

Employment constraint

The protection of employment in a certain sector is accommodated through endogenously lowering the tax on that sector's labor use. That is, in this case, the multiplier θ_{Fj} in equation (A.12) is associated with the constraint

$$L_j \geq \overline{L_j} \tag{A.21}$$

where $\overline{L_j}$ is the exogenously specified lower bound for aggregate employment, L_j, in sector j. If employment in sector j is protected, then θ_{Fj} is scaled down until the associate constraint (A.21) is satisfied.[37]

[37] The tax multiplier on labor tax, θ_{Fj}, hence consists of two multipliers, one associated with the government budget constraint and one associated with the employment constraint.

Chapter III

Bankable Emission Permits and the Control of Accumulative Pollution: A Numerical Application to Swedish CO_2 Policy

1. Introduction

There is a general consensus among economists that implementation of tradable emission permit systems can be an efficient strategy for achieving environmental goals. The fundamental concept of permit systems, which can be attributed to Dales (1968), is simple; a regulatory agency distributes emission permits to polluters in accordance with its environmental goal. The permits are then allowed to be transferable among polluters, resulting in an equalization of marginal abatement costs between pollution sources. Montgomery's (1972) seminal paper on emission permits proved that in a competitive economy, such a permit system can achieve a given emission standard at least abatement cost. Since then, numerous theoretical and empirical studies have further investigated the properties of these systems in different settings such as market power, regulated firms and imperfect enforcement.[1]

Trading emission permits through time, i.e. permit "banking" and/or "borrowing", has been given relatively less attention in the literature, however. One reason for this is that many of the properties of intratemporal[2] permit trading carry over directly to permit trading through time. Unrestricted intertemporal trading allows firms to equalize (present value) marginal abatement costs between time periods and is, hence, an efficient way of reaching a cumulative emission standard within a specified time horizon. This has been shown by, for example, Cronshaw and Kruse (1996) and Rubin (1996).

Market based instruments have become increasingly popular among environmental policy makers during the last decade. Besides emission taxes, tradable permit systems are the most commonly suggested instrument for achieving environmental goals. One reason for this is that the effectiveness of permit trading, as indicated by theoretical studies, has been empirically

[1] See e.g. Cropper and Oates (1992) for a survey.

confirmed by the successful implementation of a permit market for sulfur dioxide emissions in the United States.[3] The growing concern for global climate change and the importance of controlling anthropogenic carbon dioxide (CO_2) emissions, have resulted in numerous policy proposals suggesting tradable CO_2 permits. Most of the proposals recognize international emission permit trading as an effective means of reducing global emissions, especially due to large international differences in abatement costs and the irrelevance of where the emissions take place. Although global CO_2 permit trade is likely to effectively reduce abatement costs, it is questionable if such a system will be implemented in the near future. Several proposals thus recognize geographically restricted permit systems, such as European or single country systems, as a feasible way of achieving emission reductions. In Sweden, for example, a government commission has investigated the possibilities for Sweden of using unilateral CO_2 permit systems or be part of a trading system with neighboring countries.[4] Other countries are currently investigating the possibility of setting up their own trading systems.[5] Some of these proposals recognize the possibility of giving firms credit for emission reductions beyond what is required of them, i.e. to allow for permit banking.

Given the relatively large policy interest in tradable permit systems, surprisingly few empirical estimates of the potential cost savings from the use of intertemporally tradable emission permits are found in the literature.[6] A large number of studies have assessed the cost of emission abatement in static and dynamic multi-sectoral simulation models, but intertemporal permit trading is seldom explicitly included. Empirical assessment of the optimal abatement path, which is closely related to bankable permits, is carried out in some studies but trade in permits has not been explicitly considered. Most of these studies investigate the effects of long-term optimal greenhouse gas abatement using global, highly aggregated, general equilibrium models in the spirit of Nordhaus' (1994) DICE model.[7]

The purpose of this study is to explore and quantify the effects on abatement paths, permit price, and aggregate welfare when permits are allowed to be traded through time, i.e. if permit banking and/or borrowing is allowed. More specifically, the study numerically assesses the implications of a Swedish unilateral pursuit for reducing the domestic contribution to the accumulation of greenhouse gases by using a tradable CO_2 emission permit system. The

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[2] *Intra*temporal refers to trading within a time period, and *inter*temporal to trading between time periods.
[3] The U.S. SO_2 allowance trading program is described in e.g. Stavins (1998).
[4] See SOU (2000).
[5] See e.g. Haites et al. (2000).
[6] Among the few studies are Rubin and Kling (1993) who empirically estimate the effects of banking and borrowing in a partial equilibrium model of vehicle manufactures in California.

envisaged policy background is a setting where no international tradable permit system is established and Sweden therefore sets up a domestic trading system. The long-term policy goal is to reduce the accumulated amount of carbon in the atmosphere originating from Swedish emissions within a specific timeframe. This policy may take the form of a strict annual emission cap with only intratemporal permit trading, a system allowing for forward trading through time, i.e. banking, or finally, a system allowing for both banking and borrowing of permits.

The paper is organized in the following way. In section 2, the characteristics and determinants of an optimal abatement path and the effects of emission banking are derived by means of an analytical model. Section 3 presents an overview of the simulation model used. The results are presented and interpreted in section 4, and section 5 concludes the study.

2. Emission banking and borrowing

In intratemporal permit trade, the geographical dimension of the market is important if the damage is related to the site where the emissions take place. Analogously, if the permit system has a temporal dimension, the timing of emission is consequential if the damage has a temporal component. Kling and Rubin (1997) formally showed that bankable permits might not result in a socially desirable outcome when the environmental damage is related to the level of emission flow in a specific time period, rather than over several time periods.[8] Not unexpectedly, in such a setting trading emission permits through time could increase environmental damage, even though the intertemporal abatement goal is achieved at the lowest cost. For CO_2 emissions, however, the damage is strictly related to the accumulated carbon stock which, in turn, depreciates relatively slowly. Therefore, moving CO_2 emissions through time may be of little importance for the environmental damage as long as the accumulated stock reaches a certain target level at some future point in time. Consequently, the environmental policy goal is formulated as a specific accumulated stock that should be reached decades into the future[9], which makes CO_2 emission permits suitable for intertemporal trade.

[7] See e.g. Manne and Richel (1992), Richels and Edmonds (1995), Richels and Sturm (1996), and Goulder and Mathai (1998).

[8] See also Tietenberg (1980) for a discussion on emission permits and temporal damage.

[9] For example, the formal objective of the UN Framework Convention on Climate Change (Article 2: Objective) includes 'stabilization of GHG concentration at a level that would prevent dangerous anthropogenic interference with the climate system. Such stabilization should be achieved within a time frame sufficient to allow ecosystem to adapt naturally, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner'.

To assess the efficiency of an intertemporally tradable permit system for a stock pollutant, the starting point is to establish the properties of the optimal abatement path. The theory on this optimal path has been developed in the environmental literature, at least since Keeler et al. (1972). From this literature, it is clear that there is no general rule for dealing with stock pollution problems. Among other things, the optimal abatement path of accumulating pollution depends on the evolution of technological progress, the accumulation and depreciation of pollution, and whether uncertainty and threshold levels are present.[10] In the following analysis, however, a relatively simple version of this optimization problem is considered, disregarding many of these complications.

The optimal time path of emission permits is derived and compared with the outcome from a decentralized tradable permit system, where permit banking and borrowing are allowed. A restricted version of the permit trade system where banking but not borrowing is allowed, is also considered. A simple analytical modeling framework is used to identify the mechanisms that are important for the optimal abatement path and the outcome of a bankable permit system.[11] The model will resemble the specification applied by Kling and Rubin (1997), but is extended to deal with the regulation of a stock externality. The purpose of this section is not to give a full analytical treatment of the problem, but to derive expressions in order to aid the interpretation of the numerical results.

The setup of the model is as follows. The regulatory agency is assumed to have a single environmental goal, namely achieving a pollution stock target, $\bar{S}$, at time T. The stock pollutant accumulates in the receptor according to $\dot{S}_t = F_t - \delta S_t$, where S_t is the accumulated stock at time t, F_t is the total emission at time t, and δ is the (stock independent) natural depreciation rate of the pollution stock.[12] Furthermore, the initial stock, S_0, is assumed to be irrelevant for the policy and is therefore set to equal zero.

There are N heterogeneous price taking firms (indexed i) in the economy producing a good, y, according to the cost function of $C_{it}(y_{it}, F_{it})$. F_i is the emission of the stock pollutant that reduces the cost of production for a given production level. C is assumed to be strictly convex

[10]Goulder and Mathai (1998) have assessed the issue of technological progress. Withagen and Toman (1998) study the effect of different pollution accumulation functions on optimal abatement and Tahvonen and Withagen (1996) examine the effect of irreversibility. Newell and Pizer (1998) study the effects of uncertainty on the choice of policy instrument. Interlinked resource and environmental externalities with stock externalities are assessed in Farzin (1996).

[11] "Bankable permits" will henceforth refer to permits that can be intertemporally traded, i.e. both banking and borrowing as well as only banking. "Banking" will refer to permits that can be saved for use in future periods, and "borrowing" will refer to permits that can be moved from future to earlier periods.

[12] In the subsequent analysis a dot over a variable denotes differentiation with respect to time, and a variable in subscript (except the variable t) denotes differentiation with respect to the variable designated by the subscript.

in y and F, with the properties $C_y > 0$, $C_F < 0$, $C_{yF} < 0$. The marginal abatement cost (MAC) is the negative of C_F and therefore an increasing function of the abatement level. The total emission at time t is hence $F_t = \sum_{i=1}^{N} F_{it}$ units of the pollutant. The firms are required to possess one permit for each unit emitted. Thus, emissions are regulated by the aggregate amount of *intratemporal* tradable emission flow permits, $\overline{F}_t$, which is distributed by the regulatory agency at time t. By choosing the amount of permits to be distributed such that the relation

$$\int_0^T e^{\delta(t-T)} \overline{F}_t dt = \overline{S} \tag{1}$$

holds, the agency can be sure of the stock target being reached in period T. Any emission permit path that fulfills this requirement will be equally good from an environmental damage perspective.

Optimal distribution of permits

To find the permit path associated with the lowest welfare cost, the regulating agency maximizes the present value of the consumer surplus under the stock restriction. That is, it solves the following maximization problem

$$\max_{\substack{y_1,\dots,y_N \\ F_1,\dots,F_N}} \int_0^T e^{-\rho t} \left[\int_0^{y_t} p_t(z)dz - \sum_{i=1}^{N} C_{it}(y_{it}, F_{it}) \right] dt \tag{2}$$

$$\text{s.t.} \quad \dot{S}_t = \sum_{i=1}^{N} F_{it} - \delta S_t \tag{3}$$

$$S_T \leq \overline{S}, \text{ and } S_0 = 0 \text{ given,} \tag{4}$$

where p is the output price and ρ the discount rate. The present value Hamiltonian associated with this optimization problem is

$$\max_{\substack{y_1,\dots,y_N \\ F_1,\dots,F_N}} J = e^{-\rho t} \left[\int_0^{y_t} p_t(z)dz - \sum_{i=1}^{N} C_{it}(y_{it}, F_{it}) \right] + \mu_t \left(\sum_{i=1}^{N} F_{it} - \delta S_t \right), \tag{5}$$

where μ_t is the present value costate variable associated with the equation (3), which can be interpreted as the marginal shadow price of an additional unit of emission at time t. For an interior solution, the first-order conditions for all $t \in (0,T)$ are

$$J_{y_i} = p_t - C_{iyt}(y_{it}, F_{it}) = 0 \qquad i = 1,2,\ldots,N \tag{6}$$

$$J_{F_i} = -e^{-\rho t} C_{iFt}(y_{it}, F_{it}) + \mu_t = 0 \qquad i = 1,2,\ldots,N \tag{7}$$

$$J_{\mu} = \sum_{i=1}^{N} F_{it} - \delta S_t = \dot{S}_t \tag{8}$$

$$J_S = -\mu_t \delta = -\dot{\mu}_t \tag{9}$$

$$S_T \le \bar{S}, \ \ \mu_T \le 0, \ \ (S_T - \bar{S})\mu_T = 0 . \tag{10}$$

Equation (6) is the usual profit maximizing condition implying that each firm should adjust output until the marginal cost of output equals the price of the produced good. Condition (7) shows that, along the optimal path, each firm should adjust its emission until the present MAC equals the stock restriction shadow price, $-\mu_t$. $-\mu_t$ can be interpreted as the (present value) equilibrium permit price that will result from the optimal amount of tradable permits distributed at time t. Equation (9) shows that this permit price will grow at a rate equal to the stock depreciation rate. This is due to the fact that early emissions will depreciate relatively more and are hence, given the stock restriction, less costly than late emissions. The present value MAC should therefore grow at a constant rate over time.

To evaluate how the technology, discount rate, output price, and depreciation rate affect the optimal permit distribution path, equations (6) and (7) are totally differentiated with respect to time and solved for the emission time derivative, which yields (time index omitted)

$$\dot{F}_i = \frac{(\rho C_{iF} + \delta C_{iF} - \dot{C}_{iF})C_{iyy} + (\dot{C}_{iy} - \dot{p})C_{iyF}}{C_{iyy}C_{iFF} - C_{iyF}^2} \qquad i = 1,2,\ldots,N . \tag{11}$$

The strict convexity of the cost function implies that the denominator in (11) is positive. Given that C_{yy} is positive and C_{yF} is negative, some conclusions about the emission path can be drawn by evaluating the numerator.

The first term in the first parenthesis shows that a higher rate of discount will affect the emission path negatively. That is, discounting the future higher will make late emission reductions less expensive in present value terms and, therefore, emission reductions will be postponed. The second term in the first parenthesis implies that a higher pollution stock depreciation rate favors early emission, given the pollution stock target to be reached at a future date. Hence, emission reductions should be postponed with a higher δ. By the third term in the first parenthesis, postponing emission reductions will also be favored by decreasing MAC. That is, the development of abatement technology etc. will make emission reduction cheaper in later periods and, therefore, the amount of emission permits distributed should be relatively higher in earlier periods.

The second parenthesis simply shows that higher marginal cost of production in later periods would result in a postponement of emission reduction into the future, while if the output price increases with time, the reduction of emissions in the early periods will be favored as future output becomes more valuable.

Permit banking and borrowing

The regulatory agency can achieve the optimal abatement path described above by distributing the correct amount of intraperiod tradable emission permits in each period. However, as verified by the calculations below, the same outcome can be achieved by any permit distribution that fulfills condition (1) and allowing the permits to be both intra- and intertemporally tradable. To evaluate the effect of banking and borrowing on emissions, permit price and output path, the behavior of a single regulated firm is studied below.

The firm can freely trade emission permits intratemporally and may also bank or borrow emission permits. The banking of permits is, however, not costless to the firm. Denote the firm's purchase of emission permits at time t by q_t, with a negative value representing sales, and let h_t be the price of emission permits at time t. Furthermore, let Q_t denote the amount of banked emission permits at time t, and ρ, the firm's rate of discount. The profit maximization problem of the firm can now be written as

$$\max_{y_t, F_t, q_t} \int_0^T e^{-\rho t} \left[p_t y_{it} - C_{it}(y_{it}, F_{it}) - h_t q_{it} \right] dt \tag{12}$$

$$\text{s.t.} \quad \dot{Q}_{it} = \overline{F}_{it} - F_{it} + q_{it} - \delta Q_{it} \tag{13}$$

$$Q_{i0} = 0, \; Q_{iT} \geq 0 . \tag{14}$$

The firm hence chooses output and emission levels to maximize the present value of discounted profits. The state equation (13) says that the changes in banked emissions are equal to the permits less the emitted amount and the depreciation of banked emission permits. Banked emissions depreciate because emission in period t "uses" less of the stock restriction than emission in period $t+1$, due to the natural depreciation of the accumulated pollutant. The initial banked amount of emission is zero, and the final amount restricted to be non-negative according to (14).

The present value Hamiltonian corresponding to the problem (12)-(14) is (firm index i suppressed)

$$H = e^{-\rho t}\left[p_t y_t - C_t(y_t, F_t) - h_t q_t\right] + \lambda_t\left[\overline{F}_t - F_t + q_t - \delta Q_t\right], \tag{15}$$

where λ_t is the present value costate variable on the state equation (13). It can be interpreted as the marginal present shadow value of one additional unit of banked emission. For an inner solution, the first-order conditions for all $t \in (0,T)$ are

$$H_{y_t} = p_t - C_{yt}(y_t, F_t) = 0 \tag{16}$$

$$H_{F_t} = -e^{-\rho t} C_{Ft}(y_t, F_t) - \lambda_t = 0; \quad F_t > 0 \tag{17}$$

$$H_{q_t} = -e^{-\rho t} h_t + \lambda_t = 0 \tag{18}$$

$$H_{\lambda_t} = \overline{F}_t - F_t + q_t - \delta Q_t = \dot{Q}_t \tag{19}$$

$$H_{Q_t} = -\lambda_t \delta = -\dot{\lambda}_t \tag{20}$$

$$Q_T \geq 0, \ \ \lambda_T \geq 0, \ \ Q_T \lambda_T = 0. \tag{21}$$

Clearly, these conditions apply to all N firms in the economy. Furthermore, a clearing permit market implies that $\sum_{i=1}^{N} q_{it} = 0$ holds in all time periods. The emission and output vector and the permit price from conditions (16) to (21) will also satisfy conditions (6) to (10). Condition (16) corresponds directly to condition (6). Condition (18) states that the present value of one additional banked unit will equal the present value permit price $e^{-\rho t}h_t$, i.e. the firm will buy or sell permits until this condition is fulfilled. Based on condition (10), the marginal present shadow value of banked emissions is non-constant and changes according to $\lambda_t\delta$. The expressions (17), (18) and (20) show that, if the social discount factor equals the firm's rate of discount, the present value permit price, $e^{-\rho t}h_t$, equals $-\mu_t$ and, differentiating (18) with respect to t and using condition (20), follows the permit price path,

$$\dot{h}_t = (\rho + \delta)h_t \,. \tag{22}$$

Hence, the resulting abatement path in this decentralized banking-borrowing setup will coincide with the optimal path given by the solution to the problem stated in (2) to (4). The emission time derivative from this setup will also change according to equation (11).

Given that the only constraint is the final period pollution stock, i.e. that the chosen emission path does not affect welfare, it is clear that the decentralized emission trading permit system is welfare maximizing, given that the banking system is designed in accordance with the state equation (13).

Permit banking only

Some of the policy proposals considering intertemporal permit trade suggest that banking but not borrowing, should be allowed. Restricting trade to (forward) banking only is evidently not optimal in the setting considered here. In reality, however, borrowing might be difficult to enforce and, therefore, result in excessive use of permits in early periods that are not "repaid" at a later date. Clearly, with emission banking only, these "loan losses" will not occur. Therefore, it is also interesting to assess a borrowing constrained permit system. This is accomplished by adding a no-borrowing, or a non-negative banking, constraint, $Q_t \geq 0$ for all $t \in (0,T)$, to the firm's maximization problem (12) to (14). Solving the maximization problem with this additional constraint yields first-order conditions identical to (16) to (19). Condition (20), however, is replaced by $\lambda_t\delta + \phi_t = \dot{\lambda}_t$, where $\phi_t \leq 0$ is the present value multiplier to the no-borrowing constraint, and the no-borrowing constraint $Q_t \geq 0$ is added to condition (21). Solving for the constrained permit price path yields

$$\dot{h}_t = \begin{cases} (\rho + \delta)h_t + e^{\rho t}\phi_t & \text{if} \quad \phi_t < 0 \\ (\rho + \delta)h_t & \text{if} \quad Q_t > 0 \end{cases}, \tag{23}$$

which shows that, whenever the no-borrowing constraint is binding ($\phi_t < 0$), the rate of increase in permit price will decrease. If the constraint is non-binding, the permit price will increase with the same rate as with the unconstrained policy. Given that the firms adjust their emission levels until the MAC equals the permit price, the rate of emission reduction will decrease when the no-borrowing constraint binds. This can also be seen by deriving the emission path for the constrained problem, which yields the same emission path as in (11), but with the difference that the (non-negative) term $-e^{\rho t}\phi_t C_{yy}$ is added to the numerator.

3. The numerical model

The extent to which changes in the abatement technology and the parameters from equation (11) affect the emission path, and how costly a deviation from this path is, can be quantified by a numerical general equilibrium model. In addition, a numerical model can account for, among other things, inefficiencies in the existing tax system, interaction between taxes, investment and disinvestment over time, etc. The next part of this study is therefore concerned with the construction of a numerical model, capable of simulating the effects of the bankable emission permits discussed above.

The model used in the simulations is a dynamic small-open-economy CGE model designed to investigate environmental policies. It is dynamic in the sense that agents have perfect foresight and choose an optimal consumption-saving path over the modeling horizon. This implies, among other things, that they will choose the timing of emission abatement, including the use of alternative energy sources, that yields the lowest discounted cost of a tradable emission permit policy. By using a multi-sector model, sector-specific characteristics can be taken into consideration, thus enabling more exact calculations that are also important for the aggregate results. This section presents a non-algebraic overview of the model, including supply and demand functions for factors and products, equilibrium conditions, emission calculations and a tradable permit system. For a more detailed description of the "core" model and data, see chapter V.

Domestic producers

In each sector, the single and sector-specific output is produced using primary factors and intermediate inputs bought on perfectly competitive domestic factor markets. The sectoral outputs are transformed into goods by a fixed proportion transformation matrix.[13] The goods are sold on perfectly competitive markets, where agents take prices as given and behave in accordance with standard neoclassical utility and profit maximization assumptions.

In order to account for capital adjustment costs, the model applies a partial putty-clay production technology specification where each sector uses two forms of capital. One form of capital, "clay", is sector-specific and used in fixed proportions with other inputs. The other form, "putty", is malleable in the sense of being substitutable for other inputs and intersectorally mobile. Each sector's output can, hence, be envisaged as the sum of output from the two production technologies. At the benchmark year, an exogenously given share of capital is of the clay type. The remaining share, and capital formed by new investments, is of putty type. As the capital depreciates and new capital is formed, the clay technology will gradually be replaced by putty technology, resulting in successively higher capital malleability.

This specification reproduces empirically observed energy price elasticity characteristics, which tend to be inelastic in the short run and elastic in the long run. The specification yields a low elasticity of energy use in the short run due to the fixed proportions of energy and the non-malleable capital. In the long run, when a larger share of capital input will be malleable, the specification results in more responsive energy use with respect to differences in energy prices. Furthermore, in counterfactual scenarios, premature retirement of extant sector-specific capital will occur if the part of production technology using non-malleable capital becomes unprofitable due to, for example, increased energy taxes.

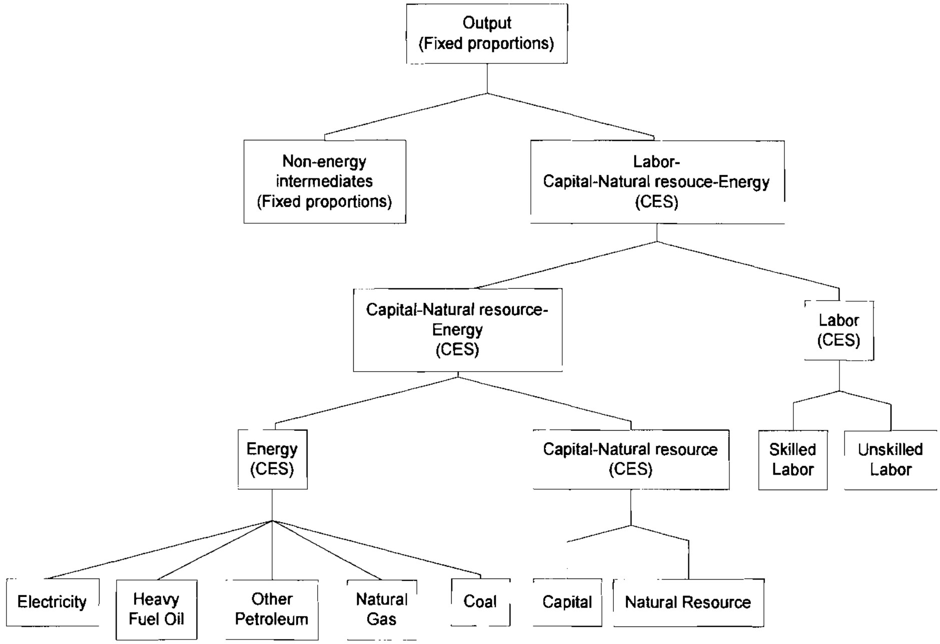
The production technology using malleable capital exhibits constant returns to scale in all sectors and is characterized by a nested constant elasticity of substitution (CES) production function, as shown in Figure 3.1. The top level is a Leontief nest where producers use different non-energy intermediate goods and an aggregate of energy goods and primary factors, unskilled and skilled labor and capital, in fixed proportions. Energy goods and capital[14] form a CES aggregate, and, at the next level, the different energy inputs form the bottom level nest. All nests, except the top-level nest, have elasticities greater than zero, reflecting a higher degree of substitutability between different primary factors and energy inputs, and also, between different types of energy goods. Both labor types are assumed to be perfectly mobile between sectors within domestic borders but internationally immobile.

[13] Two sectors (Mining and Petroleum) are treated differently. They each transform their output into (two) goods through a constant elasticity of transformation frontier. See chapter V for details.
[14] Natural resources are used by one sector (the forest sector) and included in this sector's capital nest.

The production technology using extant "clay" capital, on the other hand, lacks substitution possibilities and is, hence, represented by a single-level Leontief production function where the input proportions are the same as the ones used by the malleable production technology at the benchmark.

In addition to the technologies described above, the model allows for the inclusion of a "backstop" wind power technology producing a perfect substitute for domestically produced electricity. This production technology is modeled as a constant returns to scale, single-level, Leontief production function, producing its output using (malleable) capital, labor and intermediate goods.

Figure 3.1 Production function nesting



Import and export

Goods are sold on domestic or international markets, and the marginal rate of transformation between goods produced for the two types of markets is non-constant. Thus, the marginal rate of transformation of domestic output into export goods and domestic goods (and vice versa) is defined by a constant elasticity of transformation (CET) function.

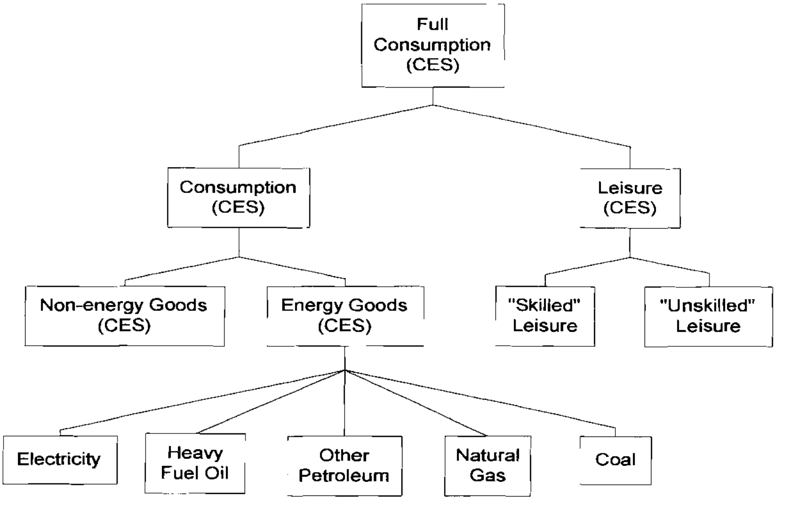
Goods for final consumption as well as intermediate inputs in production are modeled as a CES aggregate of domestically produced and imported inputs. These inputs are assumed to be imperfect substitutes according to the Armington assumption. Furthermore, the Armington elasticities are assumed not to depend on the user of the aggregate good. That is, the relative composition of imported and domestically produced goods is the same for all users.

In this model, Sweden is regarded as a small open economy. Consequently, the import supply and export demand curves are assumed to be perfectly elastic at exogenously given international prices.

Private and public consumption

The household sector is represented by a single representative, infinitely lived, consumer with perfect foresight, who maximizes a weakly separable intertemporal utility function. More specifically, the consumer maximizes the discounted sum of intra-period utility from consumption of goods and leisure over the infinite horizon, where the intra-period aggregate consumption good is the nested CES aggregate of consumption goods and leisure shown in Figure 3.2.

Figure 3.2 Intratemporal consumption nesting



The intertemporal maximization of utility is subject to a budget constraint that restricts the present value of expenditures to be less than or equal to the present value of income. The income consists of the present value of wage and natural resource income, transfers, and the value of initial capital stock endowment. Furthermore, it is assumed that the consumer can borrow and lend freely over the model horizon at the domestic interest rate.

The utility maximization can be envisaged as a stepwise procedure where the intertemporal allocation of consumption expenditures is the first step. In the next step, the intra-period utility function is maximized for each period, given the income the consumer has decided to spend in each period. Thus, the representative consumer decides how to allocate the given intra-period expenditures between consumption of goods and consumption of its effective labor endowment, i.e. leisure. It should be observed that, due to the inclusion of two labor types and one representative agent, leisure is a CES composite of "unskilled" and "skilled" leisure. Among the goods, there is first a choice between a composite of non-energy and a composite of energy goods. Finally, there is a choice between different non-energy and energy goods, respectively.

The composition of government consumption is modeled by means of a two level CES function with fixed proportions for different types of non-energy goods at the top level, and with substitution possibilities among the energy goods at the second level. The government budget is balanced intertemporally and there is no constraint on the intra-period public budget balance. In order to satisfy the intertemporal budget constraint, the level of one (exogenously chosen) tax in the model is adjusted so that the present value of expenditures is equal to the present value of revenues. Observe that the government budget constraint is satisfied by means of one single parameter, proportionally shifting the "replacement" tax in all periods.

Capital formation, investment and aggregate labor endowment

The assumption of perfect international capital markets implies that the domestic interest rate equals the world rate in steady state. The capital good is produced using Armington goods, resulting in that the domestic real interest rate may deviate from the international rate in the transition between steady states. This is due to the Armington trade specification, which makes the domestic demand curve for domestically produced goods downward sloping, and hence, the price of these goods endogenous.

Investment, I_t,, consists of a Leontief composite of Armington goods and will begin providing capital services in the following period. Thus, gross investments in period t are added to the stock of capital in period $t+1$, so that the capital stock, K, evolves according to $K_{t+1} = (1 - \delta_K)K_t + I_t$, where δ_K is an exogenously given rate of capital depreciation.

The aggregate malleable capital stock is then allocated between sectors through a capital rental-market. For the malleable capital, there is an immediate adjustment of capital allocation between sectors within domestic borders. Non-malleable capital that is installed at the benchmark year is sector-specific and hence, cannot be reallocated. This capital depreciates at an exogenous rate over the model horizon. The skilled and unskilled labor endowment is measured in efficiency terms increasing at an exogenously given (Harrod-neutral) growth rate.

The model is solved for a finite number of periods, which means that a terminal constraint must be specified in order to approximate the infinite horizon. This is accomplished by imposing a constraint on the growth rate of investment in the terminal period to equal the growth rate of consumption. That is, balanced growth is imposed but without requiring the model to achieve steady state growth.[15]

Balance of payment and Market Clearance

There is an intertemporal balance of payments constraint that equals the value of exports to the value of imports, including the benchmark capital inflow, over the simulated period. That is, international capital flows are endogenously determined in the model, and a "real exchange rate" adjusts to keep the net holdings of foreign assets constant over the model horizon.

In each time period, market equilibrium requires that supply equals demand for all traded goods. Domestically produced goods and imported goods will either be used for capital formation, as an intermediate input, be consumed by the private consumer or by the government. Similarly, factor demand equals factor supply in each period. Skilled and unskilled labor endowment equals leisure and labor input in production, and capital supply equals capital demand for malleable and sector-specific capital.

Emission flow and pollution accumulation

The model tracks the domestic flow of CO_2 emissions and the resulting carbon stock accumulation. The main part of the domestic emission of CO_2 depends on the combustion of fossil fuels. Emissions generated from combustion of one unit of a specific fuel type do not differ between users. However, due to the sector-specific composition of different types of composite fossil fuels in the model, the emission factors for these fuels types will differ across the sectors. The emissions originating from industrial processes are assumed to be proportional to the output level of the sectors in question. That is, the model includes consumer and sector-specific emission coefficients for each fossil fuel good as well as for each sector's output level.

Although the emission coefficients in a given period are fixed, the aggregate level of emissions depends on the structure of economic incentives. Thus, the emissions caused by a

[15] For a discussion of the advantage (and disadvantage) of this type of terminal constraint, see Lau et.al. (2000).

domestic consumer of fuel may change as a result of substitution between different fuels, substitution between fuels and other inputs, and changes in the activity level. These substitutions and changes in the activity level are induced by changes in relative prices, and the latter are brought about by, among other factors, changes in emission permit prices. It should be noted that the partial putty-clay specification used in the model leads to increasing substitution possibilities over time as the sector-specific "clay" capital installed at the benchmark depreciates. Therefore, emission reduction through substitution is likely to constitute a larger part of the overall emission decrease, if the reduction occurs at a later stage.

CO_2 is assumed to accumulate in the atmosphere according to Nordhaus' (1994) "two-box model", where the CO_2 stock evolves according to

$$S_{t+1} = (1 - \delta_{CO2})S_t + \alpha F_t \ . \tag{24}$$

In (24), α is the short-term removal rate and δ_{CO2} is the yearly removal rate of the accumulated CO_2 stock. That is, only a fraction, α, of the emission flow contributes to the accumulation of CO_2 in the atmosphere. The accumulated stock then depreciates at the rate of δ_{CO2} per annum. In the simulations, in accordance with Nordhaus (1994), α equals 0.64 and δ_{CO2} equals 0.008.

CO_2 permits

The regulating agency controls the amount of CO_2 emitted by requiring each emitter to possess an emission permit for every ton of CO_2 emitted. The permits are demanded by the polluting producers and consumers in direct proportion to their emission factors for fuel input, and in proportion to their output in case of process emissions. As described in the analytical model, the regulator can ensure that the pollution stock target is achieved at a predetermined year by printing and distributing a given amount of permits. The (present value) permit market equilibrium price, h_t, is established at an annual permit auction where the government collects the revenue.

If only intratemporal trade is allowed, the polluters will, equalize MAC among sectors, and among different sources within a sector. That is, they will equalize MAC of emission from different fuel inputs, emissions from industrial processes, and emissions from different production technologies.[16]

[16] Given that the emission cap is sufficiently low.

If restricted intertemporal trade is allowed, i.e. permits can be banked but not borrowed, the emitters can chose to save permits for future periods. Due to the depreciation of the pollution stock, one banked emission permit will be worth 1-δ_{CO2} permit in the next year. This implies that, in each period, the emitter will save permits if the present value permit price, h_t, is less than (1-δ_{CO2}) h_{t+1}. Therefore, the equilibrium permit price will always satisfy $h_t \geq (1-\delta_{CO2})$ h_{t+1}. Hence, with this permit system the polluters will, in addition to the intratemporal MAC equalization, also equalize present value MAC of pollution accumulation through time when $h_t = (1-\delta_{CO2})\, h_{t+1}$.

If full intertemporal trading is allowed, the emitters can choose to bank or borrow permits through time. Due to the depreciation of the pollution stock, one banked emission permit will be worth 1-δ_{CO2} permit in the next year, and vice versa for permit borrowing. In this case, the equilibrium price of the permits will not depend on permit scarcity within the current period but instead, on permit scarcity over all periods. The price of emissions will hence depend on the shadow price of the pollution (permit) stock in the succeeding period. In the model, this equilibrium price is established by recognizing that, when a polluter borrows one permit at time t, there will be 1- δ_{CO2} permit less available in period t+1. Therefore, intertemporal permit market clearance requires that the (present value) permit price h_t fulfills the condition

$$h_t = \begin{cases} (1-\delta_{CO2})h_{t+1} & t < T \\ p_t^S & t = T \end{cases}, \tag{25}$$

where p^S is the shadow price of the pollution stock restriction which is non-zero only when the cumulative amount of permits over the T periods is binding. That is, with a non-binding cumulative amount of permits, the permits will have zero value in all periods. If the price of permits in period t is lower (higher) than the price of the depreciated permit in period t+1, polluters will choose to bank (borrow) permits until equation (25) is fulfilled. With this permit system, polluters will fully equalize the present value MAC of pollution accumulation, both intratemporally and intertemporally.

Data and calibration

The model is calibrated to fit (a projection of) benchmark data for Sweden in 1993, based mainly on input-output tables from Statistics Sweden. The data tables are aggregated to correspond to detailed energy and emissions data, allowing for a disaggregation to the 17 sectors shown in Table 3.1. Sectoral aggregation is chosen in such a way that the industries are fairly homogenous with respect to emissions and benchmark environmental and energy taxation. These sectors produce 19 different goods, 14 non-energy goods and 5 energy goods (gas, electricity, coal, heavy fuel oil and "other petroleum fuels"). The division of energy goods into these categories matches differences in benchmark environmental and energy taxation of fossil fuels.

Table 3.1 Production sectors and goods in the model

Sectors	Goods
Petroleum	Heavy Fuel Oil
Agriculture	Other Petroleum Fuels
Forestry	Gas
Fishing	Coal
Mining	Mining Products
Food and Textile	Agriculture
Pulp and Paper	Forestry
Chemical	Fishing
Steel and Metal	Food and Textile
Manufacturing	Pulp and Paper
Electricity and District heating	Chemical
Water and Sewage treatment	Steel and Metal
Construction	Manufacturing
Transport	Electricity and district heating
Trade and Services	Water and Sewage treatment
Dwelling	Construction
Gas	Transport
	Trade and Services
	Dwelling

Key parameter values, shown in Table 3.2, are mainly based on econometric estimates found in the literature. Although some parameter values are associated with large uncertainties, the values used in this study do not differ substantially from those used in similar dynamic general equilibrium models. Additional assumptions concerning the growth and capital depreciation rate must be made to enable model calibration. The economy is assumed to be on its steady state growth path with an annual growth rate of 1.8 percent, which, together with the observed capital usage, investment level and an assumed annual depreciation rate of 4 percent, yields a benchline interest rate of approximately 5 percent.[17]

In addition to the energy technology in use at the benchmark, the model includes "back-stop" wind power production. Calibration of this wind power electricity technology is based on rough input share data (DEA, 1996). Furthermore, the marginal production cost is assumed to exceed the benchmark cost of electricity production with 30 percent. In addition, the

[17] See chapter V for details of this calibration procedure.

produced wind power electricity is also assumed to receive a 13 percent subsidy on gross output value.[18] Based on these assumptions, it is clear that wind power is unprofitable and, hence, remains idle in the calibrated "business as usual" (BAU) steady state. In the counterfactual scenarios where wind power is assumed to be available, however, production will start as soon as it is profitable.

Table 3.2 Key parameters used in the model

Description	Value
Steady state growth rate	0.018
Steady state depreciation rate	0.04
CO_2 stock depreciation rate	0.008
"Clay" share in putty-clay specification (All sectors)	0.90
Production[a]	
Elasticity of substitution between non-energy intermediate inputs and the composite of primary factors and energy inputs	0.0
Elasticity of substitution between labor aggregate and a composite of energy goods and capital.	0.58-0.94[b]
Elasticity of substitution between unskilled and skilled labor	1.2
Elasticity of substitution between capital and energy goods	0.17-0.98[c]
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6
Elasticity of transformation between heavy fuel oil and other fuels in the petroleum sector	4.0
Elasticity of transformation between coal and other mining outputs in the mining sector	4.0
Elasticity of transformation between goods for domestic market and goods for export market	4.0
Armington elasticity of substitution between imported and domestically produced goods	4.0[d]
Private Consumption	
Elasticity of substitution between aggregate leisure and a composite of all goods	0.5
Elasticity of substitution between skilled and unskilled leisure	0.5
Elasticity of substitution between aggregate non-energy goods and a composite of energy goods	0.4
Elasticity of substitution between different non-energy goods	1.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	1.0
Intertemporal elasticity of substitution	0.5
Government consumption	
Elasticity of substitution between different non-energy goods and a composite of energy goods	0.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6

[a)] The input elasticity values apply to the "putty" part of the partial putty-clay production function specification. The corresponding values for the "clay" part are all equal to zero except the Armington elasticities, which are equal to the same values as the "putty" part.
[b)] 0.58 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.62 in paper and pulp. 0.76 in food and textile. 0.85 in chemical. 0.87 in transport. 0.92 in steel and metal. 0.94 in mining.
[c)] 0.17 in steel and metal, 0.31 in transport, 0.49 in chemical, 0.75 in food and textile, 0.87 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, and dwelling, 0.91 in paper and pulp, and 0.98 in mining.
[d)] Equal in production and consumption.

4. Policy scenarios and results

The policy alternatives analyzed here investigate the economic consequences of the use of tradable CO_2 emission permits in Sweden. More precisely, the aim is to quantify effects on welfare and emission abatement paths from bankable emission permits in a realistic case. In the scenarios considered, the regulatory agency announces its policy in the first year of the simulated time frame, which spans 50 years. The representative agent has perfect foresight and will choose the welfare-maximizing path given the announced policy. The counterfactual

[18] The subsidy is introduced to "compensate" wind power production for the electricity tax that, in the model, is levied on electricity input.

scenarios are compared with a BAU scenario where all economic policy variables remain at their benchmark values, and the economy grows at the assumed steady state growth rate. In this reference case, the CO_2 emissions are 63.3 million metric tons in the benchmark year and grow at the same rate as the rest of the economy.

To facilitate welfare comparisons, government aggregate consumption is held constant at the BAU level over the simulated horizon in all scenarios. This is accomplished through endogenous scaling of the payroll tax in all time periods. That is, when the revenue is increased (or decreased), for example due to increased pollution permit revenues, the payroll tax will be lowered (or raised) proportionally to the benchmark rate. This implies that the calculations will include possible welfare enhancing effects from recycling of the revenue from the permit auction. All other tax rates, including energy, electricity and environmental tax rate (including the CO_2 tax), are assumed to remain at the benchmark level.

Three relatively realistic scenarios are used to evaluate the effects of allowing for emission banking and borrowing. All scenarios involve an annual distribution of tradable emission permits that meets an annual emission cap. This emission cap will fulfill an accumulated pollution stock target in the final year (year 50), which is the sole objective of the environmental policy. All emitters are required to possess one permit per unit of CO_2 emitted. That is, the permit system covers emissions from producers, including emissions from industrial processes, and emissions from final consumption.

In the first scenario, emission permits are intratemporally tradable while intertemporal trading is not allowed, i.e. an annual cap-and-trade policy. In the second scenario, permits are tradable both intratemporally and intertemporally, i.e. emitters are allowed to bank and borrow emission permits with a “banking cost” (and “borrowing premium”) as described by state equation (13) of the polluter’s maximization problem discussed in section 2. In the final scenario, permits are tradable intratemporally and bankable (at a banking cost) but cannot be borrowed.

The annual emission cap used is roughly based on the restriction placed on Sweden in the Kyoto protocol.[19] This agreement allows Sweden to increase its CO_2 emissions by approximately 4 percent relative the benchmark level. This level is assumed to apply from the first year and remain throughout the simulated time period.

The three base case scenarios are defined in the following way:

[19] The protocol to the UN Framework Convention on Climate Change concluded in Kyoto December 1997, which requires its participating countries to reach and stabilize their green house gas emission at their target levels in the period 2008-2012.

(i) *Annual emission cap* scenario, denoted AC, where the distributed annual emission permits in each year during the simulated period allows for an aggregate emission level exceeding the benchmark year level by 4 percent. Permits are intratemporally tradable but banking and borrowing is not allowed. The government distributes the permits through an annual auction.

(ii) *Banking and borrowing* scenario, denoted BB, where the permits are distributed in the same amounts and ways as in the AC scenario. Permit banking and borrowing (within the simulated timeframe) are allowed with a "banking cost" and "borrowing premium" corresponding to the natural depreciation rate of the accumulated pollution stock.

(iii) *Banking only* scenario, denoted BO, is identical to the BB scenario, but with the exception that borrowing of permits are not allowed.

In addition to these base case scenarios, a simulation where a backstop electricity production from subsidized wind power is available, and a simulation where a smaller part of production uses the rigid "clay" production structure are also carried out. The former simulation enables evaluation of banking and borrowing behavior, given that (subsidized) carbon-free electricity can be generated with a constant returns to scale technology that is unprofitable in the reference BAU scenario. Availability of a carbon free energy technology, to which substitution is gradually becoming less costly as the old capital stock depreciates, is one argument for deferring emission abatement and, hence, for emission borrowing. The latter simulation evaluates the effects of a lower adjustment cost and a slower rate of change in MAC by assuming that a larger share of the production uses malleable capital resulting in lower marginal abatement cost in all periods, especially in the beginning of the simulated horizon. This also implies that the amount of "cheap" early abatement possibilities will be larger, which is an argument in favor of allowing permit banking.

4.1 Numerical results

Aggregate abatement paths, banking and borrowing

In the BAU scenario, CO_2 emissions will, by assumption, increase at the economy's growth rate as fossil fuel consumption continues to increase with economic activity. Therefore, with a constant annual emission cap policy, the abatement is required to increase with time, starting at the date when the cap becomes binding. In the AC scenario, the emission cap becomes binding in period 3 (year 2), and abatement will thereafter increase to sustain a constant emission level. This annual cap emission path will be used as a reference when studying the abatement resulting from the BB and BO scenarios.

With a sufficiently[20] strict binding annual emission cap, intratemporal permit trade and aggregate abatement are carried out to the point where the MAC for each polluter is equalized to the shadow cost of the emission cap in that year. Clearly, with a non-binding cap, as in periods 1 to 3, the shadow cost of emission is zero and no permit trade (or abatement) takes place.

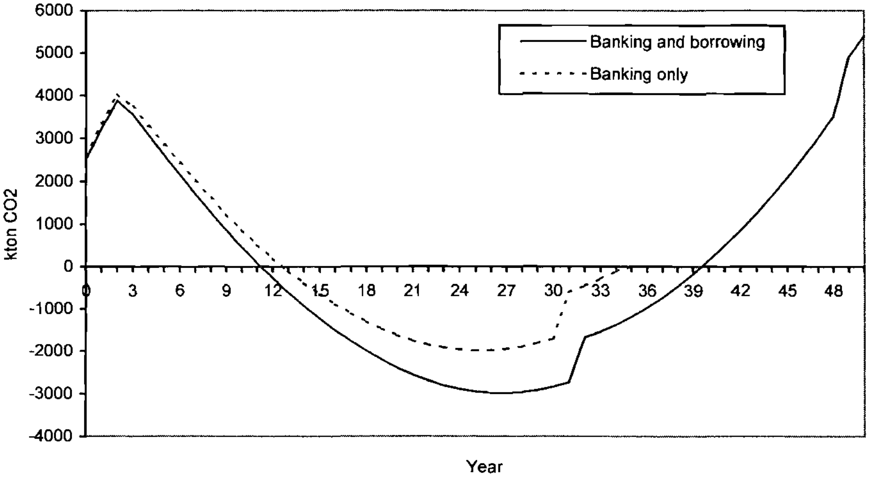
When bankable permits are used and the target accumulated pollution stock is binding, the effect of changes in the marginal abatement cost will, as was shown in equation (11), affect the abatement level in all periods. From the analytical results (equation (17)) it is clear that, if the cumulative amount of permits distributed falls short of the (accumulated) BAU emissions, abatement should start immediately. This is due to the fact that emission in the first year will have an effect on the possibilities to emit CO_2 in the future, and therefore, the shadow value of emission is positive in the first year. By not abating in the early years, "cheap" pollution stock reduction possibilities will be wasted. The simulation indicates that the resulting immediate banking will be close to 8 percent of the distributed amount of permits. This is illustrated in Figure 4.1, which shows the banking and borrowing of emission permits relative the permit use in the AC scenario. In the first year with the BB policy, permits representing 4800 kton of CO_2 will be banked, corresponding to the 7.4 percent of the benchmark emission level.[21] The BO policy results in a slightly larger amount of banked emissions in the first year.

Banking of emission permits then continues during the first 11 and 13 years in the BB and BO scenarios, respectively. That is, emission reductions will exceed the annual permit distribution as long as the positive emission shadow cost exceeds the permit price in the annual cap scenario. During the following 28 years, these permits are withdrawn from the bank, and more permits are borrowed from the final years to allow for less abatement in the intermediate period. There are several reasons for firms to borrow emission permits in the intermediate years. The early years are characterized by sharply increasing marginal abatement costs curves, due to a large share of rigid production technology. The marginal cost will decrease as the sector-specific share of the capital stock decrease. Hence, postponing

[20] That is, if the annual cap is close to the BAU emission level, the required aggregate abatement might not be sufficient to equalize MAC due to pre-policy differences in MAC among polluters.
[21] Note that in Figure 4.1 banking is compared to the use of permits in the AC scenario. In the first year in the AC scenario, the emitters will not use all permits distributed, i.e. they will "bank" permits although these permits cannot be used in the future.

abatement until a larger share of "old" technology has retired will imply cost savings for a given amount of reduction. Discounting and emission stock depreciation also favors borrowing, as was shown by equation (11). Note, however, that the amount of postponed abatement is relatively modest in relation to the total abatement level in the final years.

Figure 4.1 CO2 permit banking and borrowing (relative the annual cap scenario)



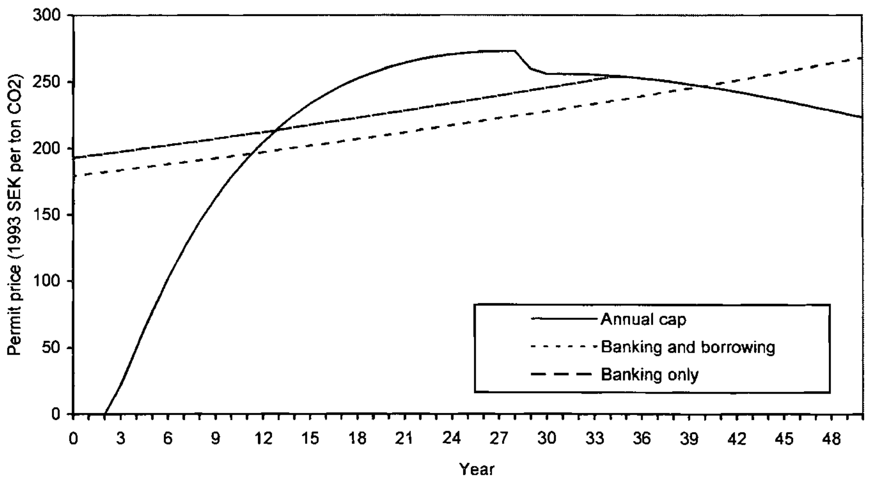
Unlike the AC policy, a decrease in MAC in one year will result in increased aggregate abatement in that year, as well as an increased amount of borrowing (and less banking) prior to that year in the BB scenario. This is illustrated by Figure 4.1, where the discrete decrease in permit borrowing in year 32 stems from a discrete reduction in abatement cost due to the premature retirement of (some) extant sector-specific capital in that year. With the BB policy, contrary to the BO policy, the firms are allowed to take full advantage of the lower MAC by postponing emission reduction.

CO_2 permit price

Figure 4.2 shows the present value CO_2 permit price corresponding to each of the three scenarios. In the AC scenario, the permits are worthless unless the cap is binding. Consequently, the present value permit price will be zero until period 3. Thereafter, the price will increase sharply as the BAU emission growth requires increasing abatement. Given the rigid production technology, most of the abatement in the early years must be accomplished through output reductions implying a high marginal cost of abatement. As the substitution possibilities increase, the marginal abatement cost will decrease, eventually resulting in a decreasing present value permit price. The kink in the permit price path indicates a discrete marginal abatement cost reduction due to premature capital retirement in one of the major polluting industries. That is, the resulting decrease in abatement cost implies that the value of permits decreases.

With the BB policy, the present value permit price will smoothly increase at a rate equal to the stock depreciation rate, as expected from the analytical results (equation (9)). Given the stock restriction, the optimal present value permit price level starts at 180 SEK_{93} per ton of

Figure 4.2 Present-value CO2 permit price



CO_2 and increases with the stock depreciation rate, at 0.8 percent annually.[22] Any change in the marginal abatement cost will be evened out through banking or borrowing, and therefore, result in a shift in the whole permit price path.

The permit price in the BO policy will, as indicated by expression (23), initially increase at the pollution stock depreciation rate. When the no-borrowing constraints binds, starting in period 35, the present value price decreases in accordance with the annual cap price. Since firms are unable to postpone abatement, banked emissions will be more valuable relative to the BB policy. Hence, the initial permit price will exceed the permit price in the BB scenario, as shown in Figure 4.2.

[22] Note that the pre-policy benchmark CO_2 tax rate is maintained in the simulations, i.e. the total cost of carbon emissions will be the benchmark tax rate plus the permit price. The benchmark *average* tax level is approximately 280 SEK per ton of CO_2 (and excludes process emissions).

Sectoral abatement paths

In addition to the aggregate permit banking and borrowing, the model also quantifies the sector-specific abatement. All scenarios indicate large intratemporal differences in emission permit use between sectors, compared to the benchmark emission allocation. One reason for this is the relatively large differences in the marginal abatement cost among polluters at the benchmark, which, among other things, is due to non-uniform CO_2 taxation. The benchmark CO_2 tax scheme, which is maintained in the simulations, includes reduced tax rates for several of the major polluting industries. Emission permits, on the other hand, are traded on equal terms among all polluters and will therefore equalize the marginal abatement costs as suggested by the analytical results.

Premature retirement of extant "old" capital, which occurs in the steel and metal sector in all policy scenarios, will result in large intratemporal changes. The scrapping of "old technology" results in reduced abatement costs in this sector. With the AC policy, the reduction results in decreased permit price in the "post scrapping years", but no change in aggregate emission levels. In the BB scenario, the permit price and the aggregate abatement level will be affected as the present value (stock depreciation corrected) MAC is equalized in all periods by intertemporal permit trading. The effect in the BO scenario will either resemble the effect with the BB policy or the effect with the AC policy, depending on whether the capital retirement occurs before or after the no-borrowing constraint binds.

By assumption, all sectors use the same proportions of "putty" and "clay" production technology but differ in their labor-capital-energy substitution elasticity. Hence, as the extant clay capital depreciates and the production, to an increasing extent, uses malleable capital, the reduction in abatement cost will differ between sectors. This change in abatement cost will cause the relative sectoral permit use to differ between time periods, given that all polluters pay the same permit price. This effect will, however, be present both with an annual emission cap and with intertemporal permit trade policy. The banking and borrowing behavior might, nonetheless, differ between sectors depending on how their MAC changes with abatement. That is, a large spread between the BB and the AC permit prices will induce large differences in abatement between the two policies in the sectors with relatively elastic MAC curves (and vice versa). The simulations, nevertheless, indicate that the relative permit banking and borrowing seem to vary relatively little between polluters, when compared with the AC policy outcome.

Aggregate welfare effects

The welfare effects from the simulations are presented in Table 4.1. The welfare measure used is the change in Hicksian equivalent variation (EV), measured as the percentage change of the present value of consumption in the simulated timeframe, relative to the present value along the steady state BAU growth path. As expected from the analytical model, the welfare cost is reduced when banking and borrowing are allowed. Thus, by taking advantage of the gains from intertemporal CO_2 emission trade, the welfare cost can be reduced. The choice of policy has, however, very little effect on the full consumption path chosen by the forward-looking consumer. The welfare gain, hence, turns out to be relatively modest in magnitude, close to 3 percent.

One reason for this stems from the gradual change toward new technology when extant capital depreciates. The resulting gradual reduction in marginal abatement cost will ensure that the annual cap restriction permit price, despite the steady increase in BAU emissions, increases in a relatively modest pace and eventually decrease in present value terms. Thus, the AC permit price will deviate less from the more constant permit price resulting from permit banking and borrowing, than would be the case with, for example, a constant high MAC. This is also verified in the analysis below. Finally, the relative welfare gain from using the BO policy is, as expected, lower than the BB policy, but only by approximately one percent.

Effects from increased capital malleability and wind power availability

As noted above, the substitution possibilities between energy goods, energy and capital, and energy-capital and labor will gradually increase over time. Therefore, emission reductions among producers in the near future will mainly stem from relatively costly output reductions. In the case of substantial cost increases due to high permit prices, premature retirement of extant clay capital might occur, resulting in an instant increase in substitutability as new capital is installed. With an assumed higher malleability of capital from the start year, i.e. with a lower clay share, the cost of the policy will be lower in all scenarios as shown in Table 4.1. Furthermore, the relative cost advantage of bankable permits decreases as the rate of change in MAC decreases. Comparing the permit price paths for the AC scenario in Figure 4.7, it is clear that the present value price path is less concave when capital is more malleable. That is, the permit price path will follow the bankable permit price path more closely. The permit price with the BB policy will, as expected from the analytical model, be reduced in all periods due to reduced marginal cost of abatement, but will still increase at the same rate as the pollution stock depreciates.

Furthermore, the effect of premature retirement of sector-specific capital will, evidently, have a much lower effect when this capital share is low. This implies a lower gain from postponing emission abatement, and therefore, less permit borrowing in the intermediate years, as shown in Figure 4.3. The immediate emission reduction will, however, be less costly and permit banking will be higher in the early periods. This, in turn, results in little difference in permit price and abatement path between the BB and BO policy, as shown in Figures 4.5 and 4.6.

Availability of carbon-free back stop technology in the form of wind power produced electricity will affect the permit banking and borrowing path in a way opposite to the case with higher capital malleability. From initially being unprofitable, the electricity produced by using wind power gradually becomes more attractive with increasing permit price and with increased use of new technology allowing for substitutability between energy inputs. With the BB policy, the wind power production will remain unprofitable until period 36. Polluters will now optimally postpone abatement, resulting in less banking in the early years and more borrowing in the intermediate years. Nevertheless, it will still be profitable to bank emissions in the first period due to the positive shadow price of the pollution stock. As expected from the analytical model, the price of bankable permits will, through intertemporal trading, be reduced in all periods when future marginal cost is decreased. Although the abatement paths differ substantially, wind power availability will, as seen in Figure 4.6, have the same effect on permit price as increased capital malleability. Both reduce the permit price by approximately 15 percent in the first year.

Banking of permits in the BO policy will be unaffected by wind power availability, as is seen by comparing Figures 4.1 and 4.4. Electricity produced with wind power becomes profitable in year 34 with this policy. However, the no-borrowing constraint will bind two periods earlier, and the lower MAC after this period will not change the permit price prior to this year. Instead, the lower MAC will reduce the permit price necessary to fulfill the binding emission cap, as in the AC scenario.

Figure 4.3 CO2 permit banking with lower rate of MAC change (lower clay share) (relative the annual cap scenario)

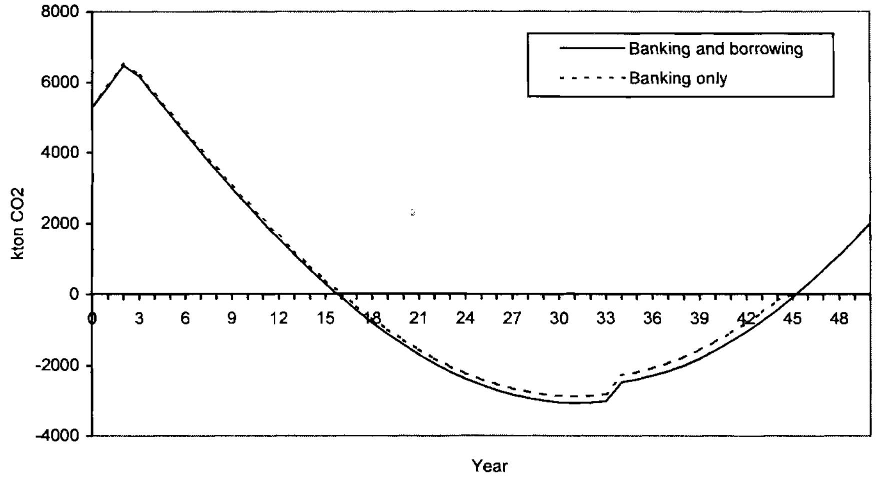


Figure 4.4 CO2 permit banking and borrowing with wind power (relative the annual cap scenario)

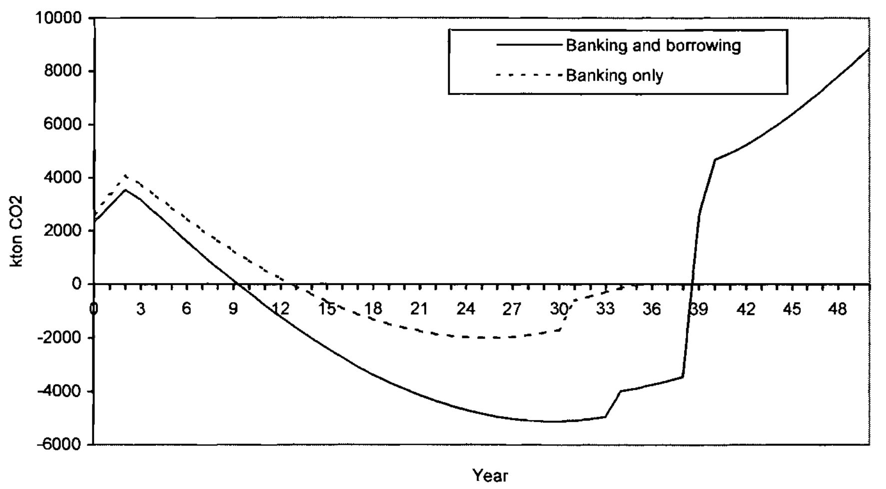


Figure 4.5 Present-value CO2 permit price with banking only

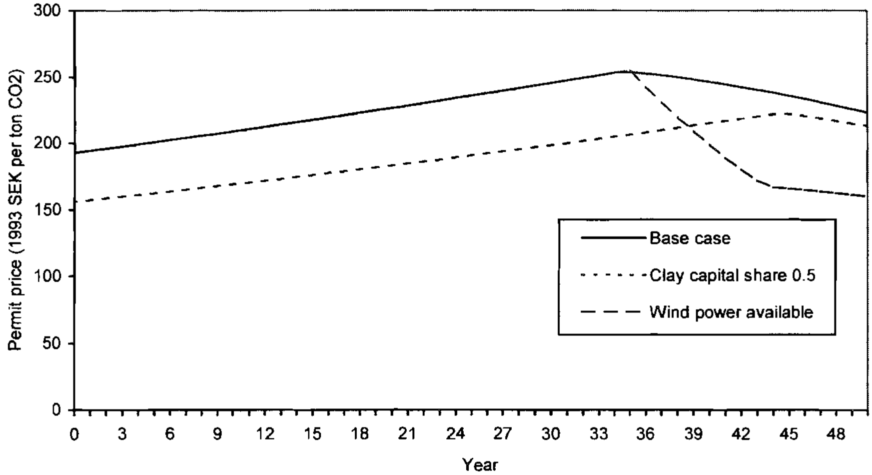


Figure 4.6 Present-value CO2 permit price with banking and borrowing

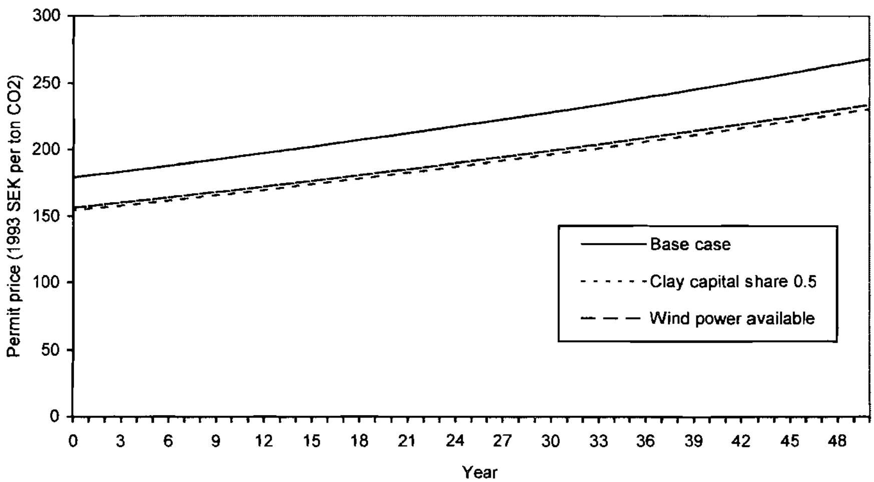
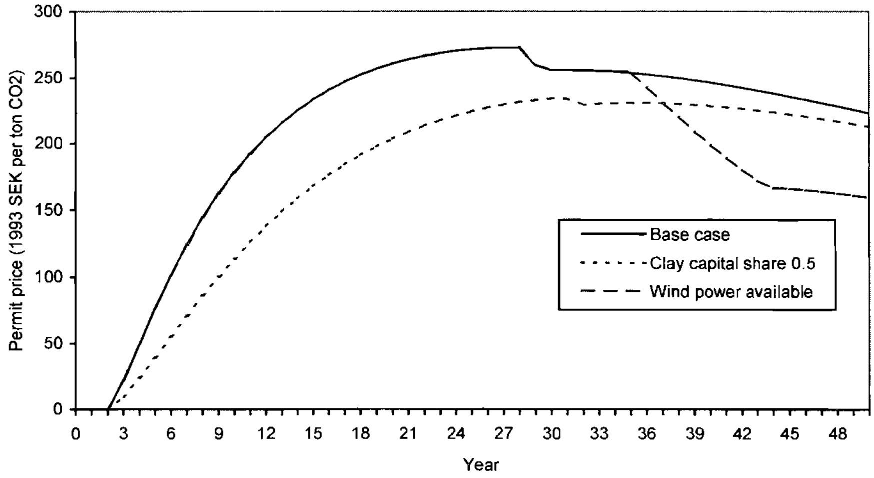


Figure 4.7 Present-value CO2 permit price with annual cap



With the AC policy (Figure 4.7), the present value permit price will be more concave relative to the base case, which indicates that higher gain from intertemporal permit trade is possible. Consequently, cost saving from using the BB policy is larger when wind power is available. The relative welfare gain is slightly more than 6 percent. The gain from using BO policy, on the other hand, is more or less unaffected by wind power availability.

One noteworthy result from the simulations is that availability of wind power technology, as assumed in the model, will result in decreased aggregate welfare relative simulations where it remains idle. This is a result of the subsidy on wind power produced electricity. Without the subsidy, the assumed wind power technology would never become profitable in the policy scenarios considered and would hence remain idle. With subsidies, however, wind power production will be profitable but the government must raise revenue elsewhere to maintain budget neutrality. In the model, this will be accomplished by an increase in the payroll tax. The welfare cost of doing this will exceed the benefits from the reduced abatement cost wind power entails.

Table 4.1 Welfare effects (EV percent of BAU present value income)

	Annual cap scenario	Banking & borrowing scenario	Banking only scenario
Base Case	-1.545	-1.497	-1.530
Lower rate of MAC decrease (50 % benchmark clay share)	-1.444	-1.433	-1.443
Wind Power	-1.610	-1.507	-1.595

4.2 Sensitivity analysis

The results presented above are, by necessity, conditional on several assumptions concerning parameter values.[23] In this section, the robustness of the main simulation results are examined with respect to some key parameter values, namely the intertemporal elasticity of substitution and the energy-capital-labor substitutability.

With lower capital-energy-labor substitution elasticity, postponing emission reduction is less beneficial. That is, when new malleable capital is installed, substitution to less carbon intensive energy and toward primary factors becomes more difficult relative to the base case simulations. Therefore, the marginal abatement cost will not decrease at the same speed and hence, according to the analytical model results, makes permit borrowing less attractive. Reducing the energy-energy, energy-capital, and energy-capital-labor elasticities by 33 percent produces results in accordance with the theoretical results (Figures 4.9 and 4.10). With the BB policy, more emission permits will be banked in the early periods and less permits borrowed in the intermediate period. Analogously, higher elasticities make permit borrowing more attractive. The effects, however, are modest.

The welfare costs of the CO_2 policies are relatively higher (lower) with low (high) substitution elasticities. Clearly, with a lower elasticity of substitution, i.e. a higher marginal abatement cost, the permit price will be higher. Figure 4.8 shows that the permit price is relatively sensitive to the elasticity value used. For example, with higher elasticities, the initial permit price is reduced by 25 percent with the BB policy. The relatively modest change in initial banking resulting from this fairly large change in permit price indicates that the aggregate benchmark MAC curve is relatively flat initially, but increases sharply thereafter. The "cheap" emission reductions will be utilized already at the low permit price and any

[23] The core model's sensitivity to production function nesting, capital malleability and other parameter values is explored in chapter V.

increase of early years permit price will, hence, have a modest effect on the amount of banked permits.

The relative welfare gain from the BB policy is lower (higher) when the substitution elasticity is low (high). The magnitude of the gain is still modest, however, 3.3 % and 2.8%, respectively.

A low intertemporal elasticity of substitution implies that the representative agent is less willing to accept deviations from a smooth consumption pattern over time, and the opposite for a high elasticity. The representative agent is, however, able to borrow and lend without constraints at the domestic interest rate, and hence, the consumption paths in the two scenarios will differ while the difference in permit banking and borrowing barely is noticeable. The effect on welfare is, as shown in Table 4.2, modest in both evaluated cases, i.e. with half and double intertemporal elasticity of substitution values.

Table 4.2 Sensitivity analysis of welfare effects (EV percent of BAU present value income)

	Annual cap scenario	Permit banking & borrowing scenario	Permit banking scenario
Base Case	-1.545	-1.497	-1.530
Lower Energy-Capital-Labor substitutability (33% substitution elasticity reduction)	-1.967	-1.917	-1.945
Higher Energy-Capital-Labor substitutability (33% substitution elasticity increase)	-1.328	-1.275	-1.316
Reduced intertemporal elasticity of substitution (0.25)	-1.549	-1.505	-1.534
Increased intertemporal elasticity of substitution (1.00)	-1.537	-1.487	-1.522

Figure 4.8 Present-value CO2 permit prices. Sensitivity w.r.t. energy-capital-labor substitutability

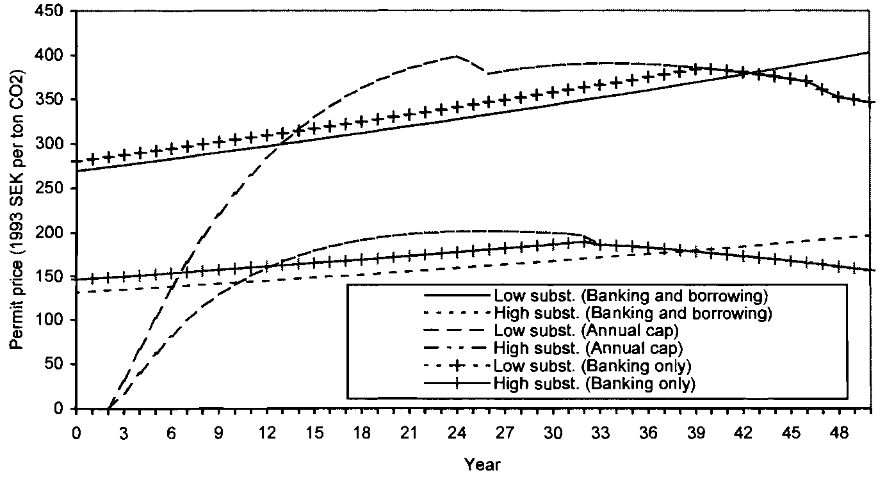


Figure 4.9 CO2 permit banking and borrowing. (relative the annual cap scenario) Sensitivity w.r.t. energy-capital-labor substitutability

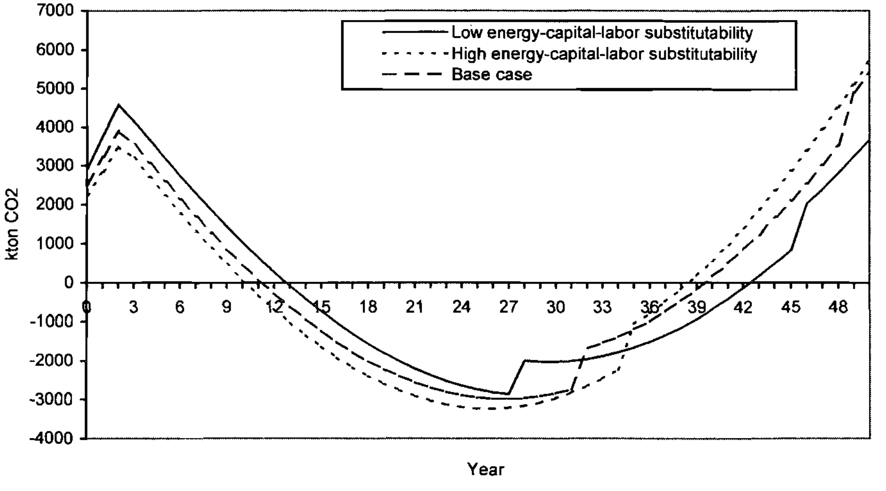
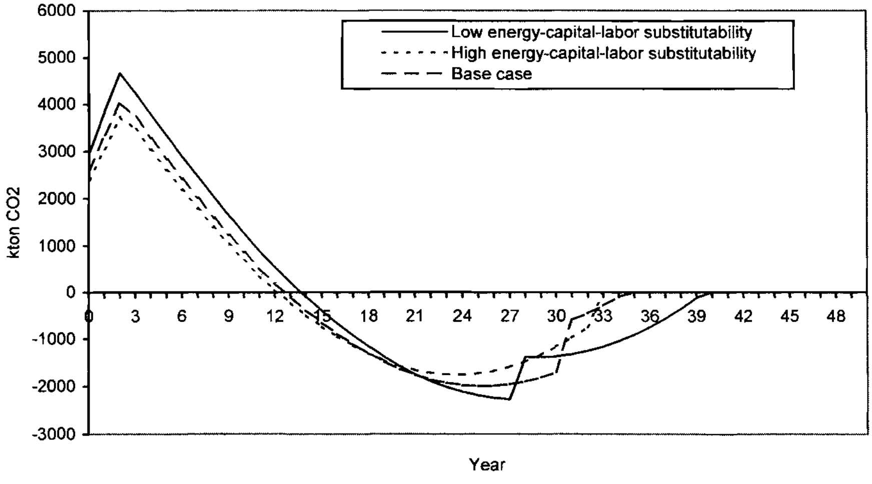


Figure 4.10 CO2 permit banking only. (relative the annual cap scenario) Sensitivity w.r.t. energy-capital-labor substitutability



5. Summary and conclusions

This paper has studied emission regulation that uses intertemporally tradable emission permits in the case where the emission path itself is of no environmental importance, given that an accumulated pollution stock target is not exceeded. Starting with a simple analytical model, it was illustrated how a decentralized system of tradable emission permits could result in an optimal abatement path toward a future pollution stock target. Such a system allows for permit banking and borrowing and also takes into consideration the natural depreciation of the pollution stock. The model was used to show how the abatement path and permit price were dependent on, among other things, marginal abatement cost and pollution stock depreciation. The effect on the abatement path and permit price when the permit system is restricted to banking, but not borrowing, was also derived.

The study continued by setting up a dynamic numerical general equilibrium model of Sweden that enabled quantification of permit banking and borrowing, permit price as well as welfare effects, in a realistic case. More specifically, the numerical simulations quantified welfare effects and the permit price path resulting from the use of intratemporally tradable permits with a constant annual CO_2 emission cap. This policy was compared with a system allowing for permit banking and borrowing, as well as a system allowing for banking but not borrowing. All three policies were constrained to reach the same accumulated carbon stock in the final year.

The simulations indicate that the welfare gain arising from a change from a constant annual cap system to a system with permit banking and borrowing is small, that is, in the order of 3 to 6 percent. Furthermore, the gains from allowing for intertemporal permit trade increase with intertemporal changes in marginal abatement cost. Thus, in simulations with the availability of wind power produced electricity, the benefits from emission banking and borrowing will be larger as polluters can borrow permits from future periods when substitution between energy sources becomes less costly. In addition, with a given wind power technology, the optimal permit price will be lower in all periods, which implies less abatement in early periods. If the permit system does not allow for borrowing, the abatement path will be largely unaffected by future reductions in the marginal abatement cost.

Compared with the constant annual emission cap, banking and borrowing will yield an abatement path where firms initially bank permits because the positive shadow cost of emissions exceeds the benchmark marginal abatement cost. Therefore, abatement, which initially amounts to about 7.4 percent of the benchmark emission, starts immediately to take advantage of "cheap" emission reduction options. These banked permits will be used and, if allowed, additional permits will be borrowed during an intermediate period. Emission abatement is thereby postponed until future periods when new technology is installed and the marginal abatement cost is lower.

Clearly, the present version of the model disregards from several potentially important issues such as uncertainty, policy-induced technological development, and international as well as global effects. A detailed (dynamic) multi-country model would be necessary to investigate some important issues concerning international pollution permit trading with banking and borrowing. The effects of policy on technological change are likely to be very important for the timing of abatement, but currently, these relationships are far from well understood. The model could, however, be extended to include "learning by doing" or "R&D" based technological progress, but the parameterization of such functions must, to a large extent, be made in an ad hoc manner.

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Chapter IV

Assessing Effects of Pollution and Environmental Policy in an Integrated CGE Framework

1. Introduction

It is well known that emissions and accumulation of pollutants in the environment, with few exceptions, have a negative effect on the quality, and thus the consumption value, of the environment. However, emissions and accumulation of pollutants also tend to reduce the supply of natural resources and/or the quality of labor and real capital, thus reducing the output of goods and services, i.e. the GDP. Conversely, emission control and abatement activities increase the output of goods and services, and thus GDP, by increasing the supply of natural resources and/or the quality of labor and real capital.

Many economists have stressed the potentially large bias from disregarding these environmental-economic interrelationships when analyzing pollution problems.[1] However, this type of interdependency effects of environmental pollution are rarely explicitly included in simulation studies using computable general equilibrium (CGE) models, or taken into account in long term economic forecasting. One obvious reason for this is that, in many instances, these relationships are intricate and far from well known. Most studies concerned with economic-environmental issues therefore use a separable, or unidirectional, specification. Glomsrod et al. (1992), Boyd et al. (1995), and Brendemoen and Vennemo (1996) are examples of studies where several environmental externalities are included in the calculations, but where the effects are all modeled as unidirectional. That is, the development of economic variables affects the quality of the environment, but changes in the quality of the environment have no impact on the development of economic variables.

In order to capture the direct and indirect effects of environmental pollution as discussed above, a non-separable, or bi-directional, specification is needed. In a bi-directional model, the effect could either affect the preference- or technology-related substitutions or the resource stock (or both). Furthermore, these effects of pollution could depend on the

[1] Ayres and Kneese (1969) and Mäler (1974) were among the first to stress this. See also Mäler (1985).

accumulated stock of pollutants in the environment, or on the current flow of emissions (or both).

Only a few empirical general equilibrium studies that endogenizes pollution damage are available in the literature, most of which disregard the fact that pollutants accumulate over time and/or specify a relatively rough feedback effect on total factor productivity. One example of a "feedback model"[2] is the global DICE model (Nordhaus, 1994) where (carbon) pollution accumulation feed back on the total factor productivity through climate change. More closely related to the study at hand are the multi-sector models used in Bergman et al. (1995) and Vennemo (1997). The former study uses an iterative dynamic model where accumulation of sulfur dioxide and total factor productivity loss are considered as well as natural resource damage and "defensive" measures. The latter study presents a model of Norwegian economy including several feedback mechanisms of local pollutants, but does not explicitly include damage effects from pollution accumulation.

The purpose of this paper is to model effects of pollution flow and accumulation in a fully dynamic framework, and to explore the quantitative significance of such effects in the context of long-term economic projections and policy evaluation in a realistic case. More specifically, this study elucidates the direct and indirect feedback effects of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) on aggregate welfare and economic growth within the frame of a dynamic CGE model of the Swedish economy. The principal aim is to develop a model framework for environmental policy evaluation, where cost and benefits are integrated by explicitly modeling the effect on primary resources used in production and consumption. The current version of the model includes several of the feedback effects considered important in Sweden today. However, given the current knowledge status of these effects and the scarcity of relevant data, it must stressed that the model should be viewed as a first tentative step towards a more complete model of the Swedish economic-environmental interaction.

The rest of the paper is organized in the following way. In Section 2 the simulation model of the Swedish economy, as well as the feedback mechanisms incorporated in the model, are described. Simulation results are presented and discussed in Section 3, and, finally, Section 4 concludes the study.

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2 A model with bi-directional economic-environmental effects will henceforth be referred to as a feedback model.

2. A model with environmental feedbacks

The endowments of resources and the durability of man-made capital are typically treated as exogenously given entities in CGE models and, therefore, implicitly assumed to be unaffected by changes in pollution levels. When modeling environmental-economic interactions the first step is to identify how pollution affected resources (and durable goods) enter into the production of goods and utility. Ideally, these resources should be modeled as separate inputs and, hence, not be part of a larger aggregate. The next, clearly very complicated, task is to specify how the resources are affected by pollution. The origin of the pollution must then be derived, which includes determining at what point in the production or consumption process the pollution discharges arise, how they are transported, and if and how it is accumulated. The final step is to specify the relevant policy options. Besides the pollution abatement at the source, the damaged resources themselves can often be augmented, or their assimilative capacity increased, by the use of resources, i.e. by using "defensive production". Although the current use such defensive expenditures is included the economic input-output data used by CGE modelers, they are normally treated as independent of pollution levels.

One of the main difficulties when constructing an explicit model of environmental feedbacks is that the model must include relatively detailed specifications of far from well-known relations between environmental and economic variables. In addition to scientific uncertainties about these relations, there is a monumental lack of relevant empirical data. In Sweden, however, recent work on establishing integrated environmental and economic accounts has resulted in relatively detailed and reliable data, which is a good starting point for environmental feedback modeling. At the same time, the use of Swedish data means that environmental problems of major concern in Sweden, but possibly of less concern in many other countries, are emphasized in this study.

The adopted modeling approach is presented in the following three subsections. In the first, the "core" CGE model, used in the non-feedback simulations, is described. In the second subsection, the feedback extension of the model is presented, including the modeling of emission, the accumulation of pollutants in the environment, and the specification of damage (feedback) functions. In addition, the modeling of abatement activities and the possibility to augment the resource base through defensive expenditures are discussed. Finally, subsection 2.3 deals with data and calibration issues.

2.1 The core of the CGE model

The model used in the simulations is a dynamic, small open economy, CGE model designed to investigate energy and environmental policies. The model version used in this study is disaggregated into 17 production sectors producing 14 non-energy- and 5 energy goods listed in Table 2.1. A more detailed description of the model and the benchmark data set can be found in chapter V of this thesis. This subsection presents an overview of the "core" of the model, i.e. factor and product supply and demand functions and equilibrium conditions. Although the description is relatively non-technical, a certain degree of algebra is necessary to allow a more detailed description of the feedback mechanisms in the following subsection.

Table 2.1 Production sectors and goods in the model

Sectors	Goods
Petroleum	Heavy Fuel Oil
Agriculture	Other Petroleum Fuels
Forestry	Gas
Fishing	Coal
Mining	Mining Products
Food and Textile	Agriculture
Pulp and Paper	Forestry
Chemical	Fishing
Steel and Metal	Food and Textile
Manufacturing	Pulp and Paper
Electricity and District heating	Chemical
Water and Sewage treatment	Steel and Metal
Construction	Manufacturing
Transport	Electricity and district heating
Trade and Services	Water and Sewage treatment
Dwelling	Construction
Gas	Transport
	Trade and Services
	Dwelling

Domestic producers

In each sector (indexed j), and in each time period t,[3] the single and sector-specific output, Y_j, is produced using primary factors and intermediate inputs bought on perfectly competitive domestic factor markets. The sectoral outputs are transformed into goods (indexed i), Z_i,

[3] In order to simplify the notation, time indices are omitted in strictly intra-period equations where misinterpretation is unlikely.

through a fixed proportion transformation matrix.[4] The goods are, in turn, sold on perfectly competitive markets where agents take prices as given and behave in accordance with standard neoclassical utility and profit maximization assumptions.

In order to take capital adjustment costs into account, the model applies a partial putty-clay production technology specification in which each sector uses two forms of capital. One form of capital, "clay", is sector-specific and used in fixed proportions with other inputs. The other form, "putty", is malleable in the sense that it is substitutable against other inputs and intersectorally mobile. Hence, the output in each sector can be envisaged as the sum of the output from two production technologies, a "clay technology" using sector-specific capital, and a "putty technology" using malleable capital. At the benchmark year, an exogenously given share of capital is of the clay type. The remaining share, and capital formed by new investments, is of the putty type. As capital depreciates and new capital is formed, clay technology will gradually be replaced by putty technology, thereby resulting in successively higher capital malleability.

The production technology exhibits constant returns to scale in all sectors, and is characterized by nested constant elasticity of substitution (CES) production functions. The total output from a sector is, as noted above, the sum of output from the putty technology (Y^m) and the clay technology (Y^{nm}). The production using malleable capital has the nesting structure shown in Figure 2.1. The top level is a Leontief nest in which producers use n different non-energy intermediate goods, A_{ij}, and an aggregate of energy goods and primary factors, VE_j, in fixed proportions, that is,

$$Y_j^m = Y_j^m\left(A_{1j},\ldots,A_{nj},VE_j\right), \tag{1}$$

where

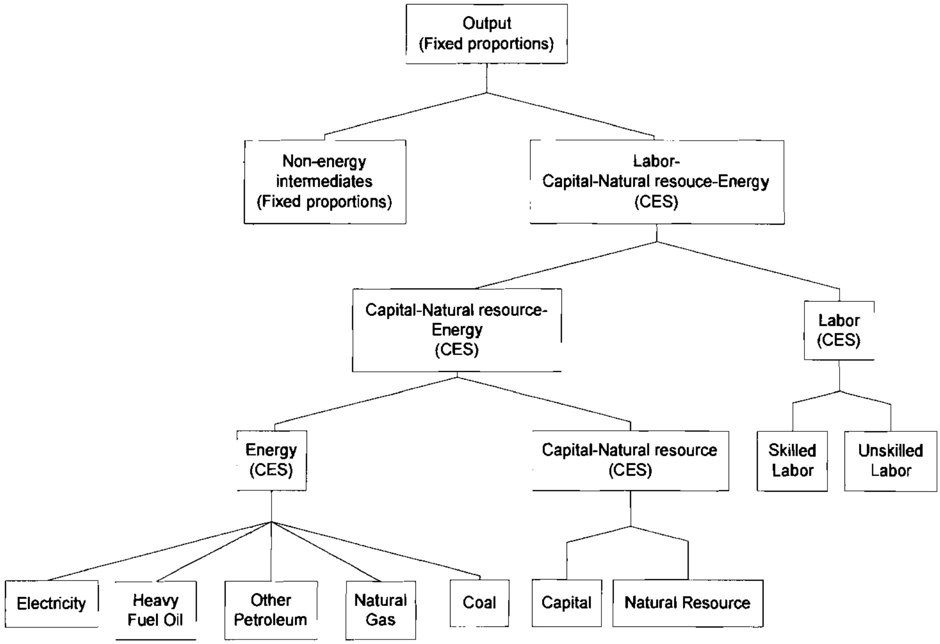
$$VE_j = VE_j\left(L_j\left(LU,LS\right),KNE_j\left(KN_j,E_j\right)\right). \tag{2}$$

LU_j and LS_j represent unskilled and skilled labor, respectively. These factors are perfectly mobile between sectors within domestic borders, but internationally immobile. KN_j is a CES aggregate of natural resources (NR_j) and perfectly mobile capital (K), and E_j a CES aggregate

[4] Two sectors (Mining and Petroleum) are treated differently. They each use a constant elasticity of transformation frontier to transform their output into (two) goods. See chapter V for details.

of different energy inputs. All nests except the top level have elasticities larger than zero reflecting a relatively higher degree of substitutability between different primary factors and aggregate energy input, and between different types of energy goods.

Figure 2.1 Production function nesting



The production technology using extant "clay" capital, on the other hand, lacks substitution possibilities and is, hence, represented by a single level Leontief production function

$$Y_j^{nm} = Y_j^{nm}\left(A_{1j},\ldots,A_{nj},LU,LS,NR_j,K_j^{nm}\right), \qquad (3)$$

where the input proportions are the same as in the malleable production technology at the benchmark.

Import and export

Goods are sold on domestic or international markets, and the marginal rate of transformation between goods for the two types of markets is non-constant. Thus the marginal rate of transformation of domestic goods, D_i, into export goods, X_i, (and vice versa) is defined by a constant elasticity of transformation (CET) function,

$$Z_i = Z_i(D_i, X_i). \tag{4}$$

Goods for final consumption as well as intermediate inputs in production, A_i, are modeled as a CES aggregate of domestically produced and imported inputs, M_i,

$$A_i = A_i(D_i, M_i). \tag{5}$$

Thus, these inputs are assumed to be imperfect substitutes according to the so-called Armington assumption. Furthermore, it is assumed that the Armington elasticities do not depend on the user of the aggregate good, i.e. that the relative composition of imported and domestically produced goods is the same for all users.

Sweden is regarded as a small open economy in this model. Consequently, the import supply and export demand curves are assumed to be perfectly elastic at exogenously given international prices.

Private and public consumption

The household sector is represented by a single representative, infinitely lived, consumer with perfect foresight who maximizes the weakly separable intertemporal utility function

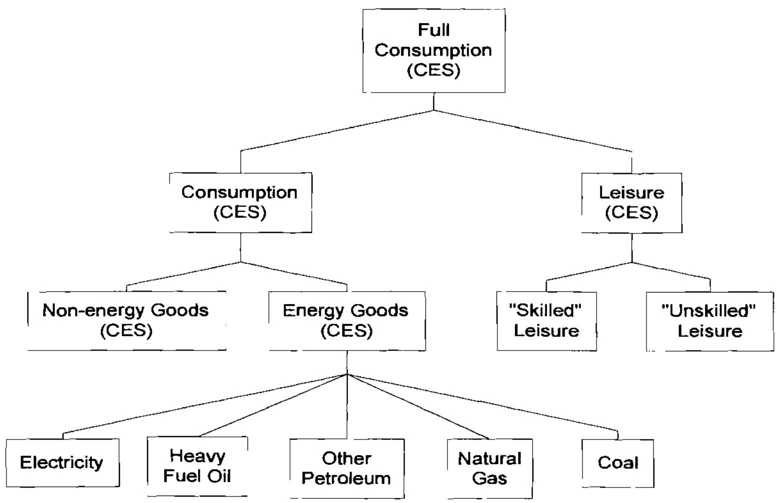
$$U(C_t) = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\Delta} \right)^t C_t^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)}, \tag{6}$$

i.e. the discounted sum of intra-period utility from (full) consumption of goods and leisure over the infinite horizon. The parameter σ is the constant intertemporal elasticity of substitution and Δ, the discount rate. The intra-period aggregate consumption, C_t, is an aggregate of consumption goods and leisure defined by the nested CES function

$$C_t = C(PC_t, L_{Ct}), \tag{7}$$

The intertemporal maximization of U is subject to a budget constraint that restricts the present value of expenditures to be less than or equal to the present value of income. Income consists of labor and natural resource payments, transfers, and the value of initial capital stock endowment. Furthermore, it is assumed that the consumer can borrow and lend freely over the model horizon at the domestic interest rate. The utility maximization can be envisaged as a stepwise procedure in which the intertemporal allocation of consumption expenditures is the first step. Then, the nested intra-period utility function, illustrated by Figure 2.2, is maximized for each period, given the income the consumer has decided to spend in each period.

Figure 2.2 Intratemporal consumption nesting



Thus, the representative consumer decides how to allocate the given intra-period expenditures between consumption of goods, PC_t, and leisure, i.e. to consume part of his effective labor endowment L_{Ct}. It should be observed that L_{Ct}, in turn, is a CES composite of unskilled and skilled labor. Then, there is a choice between a composite of non-energy goods and a composite of energy goods. Finally, there is a choice between different non-energy and energy goods, respectively.

The composition of government consumption is modeled by means of a top level Leontief function with fixed proportions for different non-energy goods and an energy goods composite, and a second level CES function that allows for substitution between energy goods. In the simulations, the aggregate government consumption is exogenously held fix to enable welfare calculations. The government budget is balanced intertemporally and there is no constraint on intra-period public budget balance. In order to satisfy the intertemporal budget constraint, the level of one of the tax instruments is adjusted so that the present value of expenditures is equal to the present value of revenues. Observe that the government budget constraint is satisfied by means of one single parameter, proportionally shifting the "replacement" tax in all periods. If the government's consumption of good i is denoted A_{iG}, and the (present value) gross of tax goods prices p_{iG}, the budget constraint can be written as

$$\sum_t \sum_i p_{iG,t} A_{iG,t} = \sum_t TR_t - T_t , \tag{8}$$

where the present value of government expenditures, on the left-hand side, equals the present value of tax and tariff revenues less subsidies, TR_t, and transfers, T_t. TR_t consists of revenue from the ad valorem goods-, factor- and value added taxation and production subsidies. All major taxes are represented in the model, including several sector and consumer specific energy and environmental taxes.

Capital formation, investment and aggregate labor endowment

A perfect international capital market assumption implies that the domestic interest rate equals the world rate in steady state. The capital good is produced using Armington goods, which implies that the domestic real interest rate may deviate from the international rate in the transition between steady states. This is due to the Armington trade specification, which makes the domestic demand curve for domestically produced goods downward sloping and hence, the price of these goods endogenous.

Investment, I_t, consists of a Leontief composite of Armington goods and will begin to provide capital services in the following period. Thus, gross investments in period t-1 are added to the stock of capital in period t so that the capital stock evolves according to

$$K_t = (1 - \delta_K) K_{t-1} + I_{t-1} , \tag{9}$$

where K_0 is given and δ_K is an exogenously constant rate of capital depreciation. The aggregate malleable capital stock is then allocated between sectors through a capital rental-market. For the malleable capital, there is an immediate adjustment of capital allocation between sectors within domestic borders. The extant "clay" capital installed at the benchmark year depreciates at the same exogenous rate as the malleable stock. In addition, this capital is sector-specific and cannot be augmented through investment.

Clearly, the model can only be solved for a finite number of periods. Therefore, a terminal constraint must be specified to approximate the infinite horizon. This is accomplished by a constraint on the growth rate of investment in the terminal period to equal the growth rate of aggregate consumption, i.e. by imposing balanced growth but *not* requiring the model to achieve steady state growth.[5]

Balance of payment and Market Clearance

There is an intertemporal balance of payments constraint so that the value of exports equals the value of imports, including the benchmark capital inflow, over the simulated period. That is, atemporal international capital flows are endogenously determined in the model, and a "real exchange rate" adjusts to keep the net holdings of foreign assets constant over the model horizon.

In each time period, market equilibrium requires that supply equals demand for all traded goods. Domestically produced goods and imported goods will either be invested, A_{iI}, consumed by the private consumer, A_{iC}, or by the government, A_{iG}, or used as intermediate input in production, i.e., in each period, clearing goods market implies that

$$A_i = A_{iI} + A_{iC} + A_{iG} + \sum_j A_{ij} \, . \tag{10}$$

Similarly, factor demand equals factor supply in each period. Effective skilled and unskilled labor endowment equals leisure and labor input in production, i.e. for both labor types indexed l

$$\overline{L}^l = L_C^l + \sum_j L_j^l \, . \tag{11}$$

Capital supply equals capital demand

$$\overline{K} = \sum_j K_j \, . \tag{12}$$

Finally, the demand for natural resource services used in production in each time period equals the endowment of that resource in the same period, i.e. for the natural resource R

[5] For a discussion of the advantage (and disadvantage) of this type of terminal constraint see Lau et.al. (2000).

$$\overline{NR}^R = \sum_j NR_j^R . \tag{13}$$

2.2 The environmental feedback model

The modeling of environmental feedbacks includes three distinct steps. The first deals with the emissions of pollutants, the second with the deposition and accumulation of pollutants in the environment, and the third with the damage to natural resources, labor, and capital, caused by environmental pollution. The damage is, in turn, divided into indirect welfare effects, i.e. effects on productivity, and direct welfare effects, i.e. effects directly affecting the consumer's utility. In addition, abatement and mitigation options are incorporated in the model.

Emission flows

The emission of two pollutants, SO_2 and NO_x are endogenously determined in the model. Domestic emissions of these pollutants depend on the use of fossil fuels and the activity levels. Emission factors differ across different types of fuels. Due to differences in (abatement) technology and the sector-specific composition of different types of composite fossil fuels, the emission factors also differ across sectors. Furthermore, there is a distinction between NO_x emissions from fuel used for transport purposes and NO_x emissions from fuel used for other purposes. Emissions originating from industrial processes are proportional to the output levels of the sectors in question. Emissions from the use of fuel types that are not explicitly modeled, e.g. biofuels, are assumed to be proportional to the output levels of each sector. Finally, imported emissions are exogenously determined in the model.

The total emission flow of a pollutant h at time t can be summarized by the expression:

$$F^h = \sum_{i \in PE} \mu_{iG}^h A_{iG} + \mu_{iC}^h A_{iC} + \sum_j \mu_{ij}^h A_{ij} + \eta_j^h Y_j + \Psi^h , \tag{14}$$

where PE denotes the set of fossil fuel goods, and μ_{ij}, μ_{iG}, and μ_{iC} are the consumer and sector-specific emission coefficients for input of good i. The parameter η_j represents the emissions from industrial processes and "other fuels" per unit of output in sector j. Imported emission *flow* is represented by the exogenous variable Ψ^h. All emission coefficients in (14) exclude emissions exported from Sweden, i.e. F^h is the total flow of pollution that will affect Sweden. Furthermore, all emission coefficients change over time in accordance with an exogenously specified (costless) technological progress in abatement technology. The emissions originating outside Sweden follows an exogenously given path over time.

Although emission coefficients in a given period are fixed, the aggregate level of emissions of different pollutants depends on the structure of economic incentives. Thus, emissions caused by a domestic fuel user can change due to substitution between different fuels, substitution between fuels and other inputs, and changes in the activity level. These substitutions and activity level changes are induced by changes in relative prices, and changes in relative prices are brought about by, among other factors, changes in energy and emission taxes. It should be noted that the partial putty-clay specification used in the model leads to increasing substitution possibilities over time as the sector-specific "clay" capital installed at the benchmark depreciates. Therefore, emission reduction through substitution is likely to constitute a larger part of the overall decrease in emission, if the reduction occurs at a later stage.

Emission deposition and accumulation

In many cases, the area within the national boundaries of a given country is a rather poor definition of the physical environment relevant from the point of view of environmental-economic analysis. In the case of green house gases, for instance, the "relevant environment" is the entire global atmosphere. In the case of SO_2 and NO_x, on the other hand, it is necessary to distinguish between different receptors within the country. For example, the impact of acid deposition clearly differs between forest land, agricultural land, lakes and rivers, and urban areas. Furthermore, the effect of emissions will also differ depending on who emits the pollutant, e.g. low altitude emissions of NO_x from transportation in densely populated areas is likely to cause more health damage than high altitude emissions in rural areas.

In the model, four different domestic receptors (indexed q) are distinguished, namely forest land (FL), agricultural land (AL), urban areas (UA) and lakes and rivers (LR). Emissions, F^h, are assumed to be deposited in the different receptors in fixed proportions. This implies that emissions originating from foreign sources are distributed between receptors in the same proportions as those originating within Sweden.

Pollutants accumulate in forest land and agricultural land. As a result, the stock of pollutant h in receptor q evolves according to

$$S_t^{hq} = S_{t-1}^{hq} + \varphi^{hq} F_t^h - \delta^{hq} \qquad q = FL, AL, \tag{15}$$

where S_0 is given and φ^{hq} and δ^{hq} are the receptor and pollutant specific deposition factor and the annual "pollution neutralization" respectively. The pollution neutralization capacity is assumed to be constant and hence, independent of the accumulated stock. That is, the degradation *rate* is decreasing with the accumulated pollution stock. This is a rough but reasonable assumption for pollutants, receptors and accumulation intervals considered here but not a good description of the accumulation of all pollutants. Increasing or decreasing assimilative capacity of the receptor with an increased pollution stock might be a better characterization of some pollutants and receptors.

Indirect feedback effects

Given the pollution flow, deposition and the receptor specific accumulation path, the link to production remains to be specified. The first step is to identify the user of the natural resource in question. Given the division of the receptors, some sectors are easily identified as potentially affected resource users, e.g. the forestry and the agricultural sectors. Identifying sectors influenced by emission flow and deposition in urban areas is, however, less trivial.

One limitation of the current model version is that it only treats damages resulting from SO_2 and NO_X emission. However, several negative effects originating from these pollutants have been identified, e.g. health effects, acidified lakes, decreased forest and crop growth and quality, increased corrosion of metals, and deterioration of stone and paint on buildings. There have been attempts to quantify all these effects in Sweden, but their inclusion into a CGE model is not straightforward. The remainder of this section describes the feedback mechanisms included in the present version of the model. A summary of these mechanisms is given in the next subsection.

Forest growth effects. One potentially important issue in Sweden is the effect on forest growth due to accumulation of sulfur and nitrogen in forest land. Some scientists claim that Swedish forest will suffer a considerable decline in quality and growth rate if the accumulation of acidifying substances continues to grow to elevated levels.[6] There exist several ecological models that simulate such growth effects on forests. Given that the CGE model tracks the accumulation of acidifying substances, data from such forest growth models will enable the inclusion of a (crude) link to production that uses the forest resource.

It should be noted that the forest stock is not explicitly modeled, and that the endowment is treated as a resource flow (annual felling of round wood). Therefore, in any year, the model

[6] See e.g. Nihlgård and Sverdrup (1993).

excludes the possibility of using more (or less) forest resources than the growth in that year, i.e. the possibility of decreasing (or increase) the aggregated forest stock.

Unless the defensive activity (described below) is used, the link between the acidifying stock at time *t* and the forest endowment at time *t* is included in the model by the equation

$$NR_t^R = \Phi_t^R\left(\mathbf{S}_t^{FL}\right)\overline{NR}_t^R \qquad R = forest, \tag{16}$$

where Φ_t^R is a function of the acidifying stock vector, $\mathbf{S}^{FL}$, i.e. the accumulated sulfur stock and nitrogen stock. NR_t^R is the actual annual harvest from the forest resource at time *t*, and $\overline{NR}_t^R$ is the corresponding reference path value. That is, the left-hand side in equation (14) is now endogenously determined in the model. Φ_t^R is specified as a linear function of the acidifying stock which, in turn, is linear in the stock of each acidifying pollutant. Hence, there is no interdependence between pollutants and the marginal damage of sulfur accumulation is assumed to be independent of the nitrogen stock and vice versa. However, the acid stock threshold level, $\overline{S}^{FL}$, under which there is no damage to forest growth, depends on the sulfur *and* nitrogen stock, i.e. the level of the sulfur stock under which there is no forest damage depends on the nitrogen stock level and vice versa. In the model, this relation is also specified as a linear function of nitrogen and sulfur stock. Hence, Φ_t^R can be written as

$$\Phi_t^R = \alpha^R - \sum_h \gamma^{hR} S_t^{hFL} \qquad \text{if } \sum_h \gamma^{hR} S_t^{hFL} \geq \overline{S}^{FL} \qquad R = forest, \tag{17}$$

where α and γ parameters are chosen in the calibration process described below. If the acidifying stock falls below the threshold level, $\overline{\Phi}^R = \alpha^R - \overline{S}^{FL}$ will set the upper limit on the possible relative forest growth increase, i.e. the forest damage at the undamaged forest endowments path relative to the model's reference path.

This relatively simple specification enables the calibration of the damage to roughly correspond to the outcome from simulations with a forest growth model. Clearly, in reality the relationship is likely to be more complex. However, given the current knowledge status and the relatively crude representation of natural resources use in the model, it is questionable if such a specification would lead to more accurate results.

Defensive expenditures in forests. The acidification of forests, agricultural land, lakes and rivers can all be counteracted by an increased use of liming. Liming of forests is only used at an experimental level in Sweden today, but large scale liming of forest land has been proposed by, among others, the National Board of Forestry. In the model, forest liming is assumed to be able to fully counteract the negative effects of acidifying pollutants.[7] The liming sector in the model uses a constant return to scale technology, with fixed proportions of capital, skilled and unskilled labor, and intermediate input (limestone), to augment the natural resource affected. That is, a perfect substitute for the forest resource,

$$Y_{Def,t}^{FL} = Y_{Def,t}^{FL}\left(K_{Def}^{FL}, LU_{Def}^{FL}, LS_{Def}^{FL}, A_{Def}^{FL}\right), \tag{18}$$

is produced using primary factors and intermediate inputs. The activity level, Y_{Def}^{FL}, is associated with the zero profit condition for the constant returns to scale liming activity. This implies that, unless the liming activity is profitable, it will be inactive.[8]

The total forest endowment equation, which replaces (16) if there is a possibility to counteract damages, can hence be written as

$$NR_t^R = \Phi_t^R\left(\mathbf{S}_t^{FL}\right)\overline{NR_t}^R + Y_{Def,t}^{FL} \qquad R = forest. \tag{19}$$

Adverse effects on capital. Deposition of acidifying substances is known to contribute to corrosion of metals and deterioration of stone and paints on buildings, vehicles, and cultural objects.[9] The deposition of sulfur and nitrogen will therefore increase the rate of capital depreciation. This is almost solely a flow effect and is, hence, modeled as being a function of the SO_2 and NO_x emission flow. The (malleable) capital stock equation (9) is consequently extended to include the corrosion effect:

$$K_t = \left(1 - \delta_K - \delta_{Corr}(\mathbf{F}_{t-1})\right)K_{t-1} + I_{t-1}, \tag{20}$$

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[7] It should, however, be noted that some researchers do not see liming as a permanent solution to the acidification problem, since several negative side effects are likely to arise. The effect from lack of liming possibilities is examined in the sensitivity analysis (section 2.3).

[8] In addition, if there is no damage due to acidification, increased use of liming can, obviously, not increase the forest resource, i.e. Y_{Def}^{FL} is restricted to be active only if $\Phi_t^R \leq \overline{\Phi}^R$.

[9] See e.g. Andersson (1994).

where the δ_{Corr} is the "extra" depreciation rate caused by changes in deposition of acidifying substances described by:

$$\delta_{Corr,t} = \sum_h \gamma^{h,Corr}(F_t^h - F_0^h), \tag{21}$$

where the γ:s are damage relation parameters. The depreciation rate of the extant part of the sector-specific capital stock will, analogously, also change with changes in δ_{Corr}. This implies that the damage caused by the benchmark emission level is included in δ_K, and that increased (decreased) emission from that level will cause an increase (decrease) in the rate of capital depreciation. The feasible reduction in capital depreciation is, of course, bounded by the total corrosion damage present at the benchmark.

Labor productivity. The flow of pollutants, such as NO_x and SO_2, has been shown to have negative effects on human health.[10] This, in turn, will cause an increase in the number of sick days, lower productivity when at work, early retirement etc. In other words, it will reduce the effective labor endowment both used in the production of goods and that is consumed as leisure. Quantifying these effects is difficult, and specifying future damage paths is even harder, due to limited knowledge of long-term effects and future progress in counteracting the damage. With rough estimates of the current pollution flow effects on effective labor, together with assumptions about the marginal damage, a simple relationship can be specified between the emission flow and efficient labor endowment. Of the pollutants included in this model, only the flow of NO_x emission can be considered a direct threat to human health in Sweden today, and then mainly due to emission from transports in densely populated areas. If F^{NO_xUA} denotes this emission flow, the feedback onto labor productivity is described by

$$L_t^{Tot} = \begin{cases} \left(\overline{\Phi}^L - \gamma^L\left(F_t^{NO_xUA} - \overline{F}^{NO_xUA}\right)\right)\overline{L}_t^{Tot} & \text{if} \quad F_t^{NO_xUA} \geq \overline{F}^{NO_xUA} \\ \overline{\Phi}^L \overline{L}_t^{Tot} & \text{if} \quad F_t^{NO_xUA} < \overline{F}^{NO_xUA} \end{cases} \tag{22}$$

where L_t^{Tot} is aggregate efficient labor endowment at time t, and $\overline{\Phi}^L$ and γ^L are parameters corresponding to the benchmark total and marginal damage, respectively. This endowment will differ from the reference aggregate labor growth path, $\overline{L}_t^{Tot}$, depending on the health

[10] See e.g. Burtraw et al (1997) and Leksell and Lövgren (1995).

reducing flow level of NO_x at time t. Pollution flow levels below the exogenously given level $\overline{F}^{NO_xUA}$ have, however, no negative impact on aggregate labor productivity. Note that the negative effect on labor endowment also affects the labor that is "repurchased" as leisure time, i.e. the NO_x flow also has a direct effect on welfare.

Direct feedback effects

Direct feedbacks are based on the change in the aggregate subjective valuation of environmental services. These effects could either be calculated as the decrease in stated valuation due to environmental degradation, or as the cost of preventing degradation and, hence, keeping the valuation (approximately) unchanged. The two measures do, however, not necessarily coincide. In the model calculations that follow, both approaches are taken.

Two main environmental goods related to acidification are considered: the "recreational" value of forests and the "recreational" value of rivers and lakes. The valuation is based on stated valuations of the whole good, and some relatively crude assumptions concerning the marginal valuation are necessary to arrive at numbers that can be included in the model. Due to data restrictions, these direct effects on recreational goods are included in the utility function as a separable effect, i.e. the total utility function including "recreational consumption" is

$$W(C_t, RV_t) = U(C_t) + \sum_R \sum_t RV_t^R , \tag{23}$$

where RV_t^R is the present value of recreational consumption of resource R at time t. Thus recreational consumption does not affect the consumer's maximization problem and, hence, does not affect the economic equilibrium. The possibility to counteract the effects of acidification, however, is explicitly included in the model, and will therefore affect the economic equilibrium outcome as well as the (separable) recreational value.

The feedback on recreational valuation of forest is included as separable from other consumption. The representative consumer is endowed with the environmental services in accordance with the stated total valuation. This value is a function of forest quality, i.e. a function of the accumulated acidifying stock and the amount of defensive expenditures used. That is, the effect on the recreational value of forest is described by

$$RV_t^R = \upsilon_t^R\left(\mathbf{S}_t^{FL}, Y_{Def,t}^{FL}\right)\overline{RV}_t^R \qquad R = forest, \tag{24}$$

where $\overline{RV}_t^R$ is the total benchline recreational valuation of forest resources. Due to the lack of marginal valuation estimates, the effect on forest growth is assumed to have a proportional effect on recreational valuation. Furthermore, the use of defensive expenditure is assumed to reduce the negative effect on the valuation in the same way as it reduces the negative effect on forest growth. The recreational relation is therefore specified as $\upsilon_t(\cdot) = NR_t^R / \overline{NR}_t^R$. Note that the decision whether to use defensive expenditure or not, is taken by forest owners based on the value of forest harvest only, i.e. the positive effect on recreational valuation is external to the owners.[11]

The acidification of lakes can be counteracted by the use of liming, which, to some extent is already in use in Sweden today. Cost estimates suggest that liming of lakes with existing technology, with a wide margin, falls short of the benefit suggested by the willingness-to-pay studies. Therefore, the decrease in recreational value of rivers and lakes is fully counteracted by liming in the model.[12] That is, increased acidification of lakes and rivers results in increased use of liming until the recreational value is fully restored.

In the model, similarly to the defensive forest liming activity, this is achieved by using a constant returns to scale defensive production, Y_{Def}^{LR}, which uses capital, labor and intermediate inputs in fixed proportions to counteract the damage. Contrary to the liming of the forest, there is no market for lake liming. Instead, based on the current practice of liming in Sweden, this is included as a public good supplied by the government and financed by tax revenues. This implies that the government "demands" lake liming and, furthermore, that increased acidification will necessitate changes in tax rates to fulfill the governments equal yield constraint. The government's budget constraint in the core model (equation (8)) is therefore extended to the following expression:

$$\sum_t p_{GVT,t}\overline{GOVT}_t = \sum_t TR_t - T_t - p_{Def,t}^{LR}\hat{Y}_{Def,t}^{LR}. \tag{25}$$

[11] The positive (external) effect on recreational valuation from forest liming also includes effects on the quality of lakes and rivers discussed below.

[12] This cost-"willingness to pay" (WTP) relation may, clearly, not hold for all acidification levels. However, the wide margin present at the benchmark is assumed to be sufficient for the WTP to exceed the "defensive" cost at all pollution levels in the simulations.

The expression on the left-hand side is the present value of aggregate government consumption along the reference path, and p_{Def}^{LR} is the present value unit cost of liming which, in each period, is determined by the associated zero profit condition. $\hat{Y}_{Def,t}^{LR}$ is the level defensive production necessary to sustain the recreational value.

To facilitate welfare calculations, the government consumption on the left-hand side in (25) is held constant through endogenous scaling of one of the tax instruments as described in section 2.1. The negative effect of lake acidification will therefore be equal to the cost of raising public funds and the diversion of inputs into the defensive production sector.

The acidification of lakes and rivers is to a large extent a function of the acidification of the surrounding land, rather than the direct deposition of acidifying particles on the water itself. Therefore, in the model, the defensive lake liming necessary to counteract pollution will depend directly on the accumulated level of acidifying substances in the forest land. That is, the level of defensive production necessary to sustain the recreational value of lakes and rivers is described by:

$$\hat{Y}_{Def,t}^{LR}(\cdot) = \Phi^{LR}(S_t^{FL}, Y_{Def,t}^{FL}). \tag{26}$$

It follows that, if liming is used to counteract acidification of the forest, the need for liming of lakes will be reduced. Therefore, the level of defensive expenditure on lake liming also depends on the level of defensive expenditures in the forest, $Y_{Def,t}^{FL}$.

Finally, the equilibrium conditions must be extended to account for the intermediate inputs, labor and capital used by the defensive activities in forest land and lakes and rivers. The market clearance conditions (10), (11) and (12) are therefore changed into

$$A_i = A_{iI} + A_{iC} + A_{iG} + \sum_j A_{ij} + \sum_q A_{iDef}^q, \tag{27}$$

$$L^l = L_C^l + \sum_j L_j^l + \sum_q L^{lq}_{Def}, \tag{28}$$

$$K = \sum_j K_j + \sum_q K_{Def}^q. \tag{29}$$

2.3 Summary of environmental feedbacks, data and calibration issues

Feedback data and calibration

The figures used in the feedback functions are all based on estimates for Sweden. Most of the numbers are retrieved from studies carried out within the project Swedish Environmental and Economic Accounts (SWEEA) (NIER, 1998a). It should be emphasized that the environmental damage numbers are associated with substantial uncertainty, and, in addition, some relatively crude assumptions are necessary to adapt the numbers into the form that fits into the modeling framework.

Forest growth effects. Some scientists argue that Swedish forests will suffer a considerable decline in growth rate and quality if the ongoing acidification of forest soils continues. To a large extent, the effects are due to pollution accumulation originating from anthropogenic emissions of SO_2 and NO_x. Although no clear empirical evidence of reduced forest quality and growth exists today, results from simulation models indicate that the future loss in forest productivity due to acidification may be substantial.[13] Simulation with one of these models, presented in Skånberg (1994), quantifies possible future forest growth reduction paths for given emission paths. By using the same assumptions about the growth rate of emissions, assimilating capacity, and critical loads of nitrogen and sulfur accumulation, the feedback effect is calibrated to produce the same forest growth rate path as was found in that study. One of the assumptions made is that the benchmark year forest soil acidification is close to the critical value, where further accumulation will result in lower forest growth rate.

Liming of forests. One way of mitigating the negative effects of soil acidification, besides emission reduction, is liming. Although liming effectively reduces the negative effects on forest soil, its long-run effectiveness and side effects are still, to a large extent, unknown. In the model, however, liming is assumed to counteract acidification also in the long run, and negative side effects are disregarded. It is assumed that liming can be used to help the forest soil directly neutralize the yearly deposition. That is, liming, modeled as a Leontief technology, prevents the forest growth decline in one single year if used in proportion to the change in accumulated acidifying stock in that year. The benchmark cost of "producing" the natural resource is therefore the cost of neutralizing one unit of acidifying substance divided by the value of the decline in forest endowment caused by that unit.[14]

[13] See e.g. Sverdrup et al. (1994).

[14] The figures used for the defensive production are very rough cost estimates from the experimental liming of forests currently undertaken in Sweden (National Board of Forestry, 1994). It is assumed that in the benchmark

Recreational value of forest. The feedback on the recreational value of forests is modeled as separable from other consumption. Total valuation of recreational activities in forests is available from willingness-to-pay studies. The total annual valuation is estimated to be around 19 billion SEK (NIER, 1998b). Due to limited data on marginal valuation, the marginal willingness to pay for increased forest quality is assumed to be constant, and forest quality is assumed to be directly proportional to the damage on forest from the accumulation of acidifying substances. Hence, the change in recreational valuation depends on accumulated acidifying stock in forest land as well as the amount of defensive liming used in the forests.

Adverse effects on capital. Acid rain and deposition of acidic particles are known to contribute to corrosion of metals and deterioration of stone and paint on buildings and vehicles. The feedback relationship included in the models is based on total and marginal cost estimates presented in Andersson (1994). The cost is modeled as an increase in the capital depreciation rate and calibrated in accordance with cost data presented in that study.

Labor productivity effects. The direct health effects of SO_2 emissions are considered to be very small in Sweden today. This is, however, not the case with NO_x emissions, which primarily affect health in densely populated areas, especially due to emissions at low altitudes. Therefore, only domestic NO_x emissions from transport contribute to the negative health effects in the model. This lowers the aggregated labor endowment measured in productivity units, due to, among other things, increases in the number of sick days and thereby affecting both the production of goods and services and leisure consumption. The model is calibrated based on total cost estimates presented in NIER (1998b).

Recreational value and liming of lakes. The acidification of lakes and rivers decreases the recreational value of these resources. Valuation studies (Silvander, 1991; NIER, 1998b) indicate a recreational value in the range of 1 to 9 billion SEK annually, and that acidification would substantially reduce this valuation. Liming of lakes will effectively reduce the negative effects on lakes and rivers. The cost of liming (all affected) lakes has been estimated, and falls short of the willingness to pay by a wide margin (NIER 1998b). There is, however, no consumer or producer demand for lake liming in the model, since lakes are used for recreational purposes. Instead, this type of defensive production is modeled as a public good demanded by the government in an amount necessary to fully counteract the negative effects. The government will raise the tax revenues necessary to finance the liming without changing

year 4 tons of limestone will neutralize the effect of 1 ton of deposited sulfur, and that the cost of applying one ton of limestone is 300 SEK_{93}.

its consumption of other goods. That is, expenditures on liming will be added on top of the expenditures on consumption, which is exogenously specified to remain constant.

The lake liming is produced with a Leontief technology. The total cost for liming all acidified lakes is based on cost estimates presented in NIER (1998b). The amount of lake liming necessary to counteract a *marginal* increase in deposition is, in turn, based on rough estimates on the area of lakes that needs to be treated if deposition remains at the present level. The acidification of a lake is not primarily due to deposition of acidic particles on the lakes itself, but to the acidity of the surrounding land. Therefore, the need for liming of lakes is modeled as a function of the soil status in the surrounding (forest) land, i.e. it is assumed to depend on the accumulation of acidifying substances in the forest soil as well as the amount of forest liming used.

Economic and pollution data and calibration

The model is calibrated to fit (a projection of) benchmark economic data for 1993, mainly based on input-output tables from Statistics Sweden. The environmental and economic accounts of Sweden (SCB, 1995, 1996) allow for a 17-sector disaggregation level shown in Table 2.1. In these accounts, the sectors are aggregated in such a way that they should be fairly homogenous with respect to emissions. Among the goods produced are 5 energy goods; gas, electricity, coal, heavy fuel oil and ”other petroleum fuels”. The division of energy goods into these categories matches differences in benchmark environmental and energy taxation of fossil fuels. In addition to the benchmark data, the calibration process requires some parameter values to be set exogenously. Table 2.2 shows the key parameter values used in the simulations. Given the steady state growth and capital depreciation rate, the SAM is projected into the future to generate the baseline data in which all quantities grow at the exogenously specified growth rate, and all present value prices decay at the interest rate.

Sector and fuel specific emission coefficients are based on unpublished calculations by Statistics Sweden. Deposition and accumulation figures for nitrogen and sulfur are based on calculations by Skånberg (1994) and Langner et al. (1996).

Table 2.2 Parameters and elasticities used in the model

Description	Value
Steady state growth rate	0.018
Steady state depreciation rate	0.04
Annual NO_x emission efficiency improvement	0.008
Annual SO_2 emission efficiency improvement	0.005
"Clay" share in putty-clay specification (All sectors)	0.90
Production[a]	
Elasticity of substitution between non-energy intermediate inputs and the composite of primary factors and energy inputs	0.0
Elasticity of substitution between labor aggregate and a composite of energy goods and capital.	0.58-0.94[b]
Elasticity of substitution between unskilled and skilled labor	1.2
Elasticity of substitution between capital and energy goods.	0.17-0.98[c]
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6
Elasticity of transformation between heavy fuel oil and other fuels in the petroleum sector	4.0
elasticity of transformation between coal and other mining outputs in the mining sector	4.0
Elasticity of transformation between goods for domestic market and goods for export market	4.0
Armington elasticity of substitution between imported and domestically produced goods	4.0[d]
Private Consumption	
Elasticity of substitution between aggregate leisure and a composite of all goods	0.5
Elasticity of substitution between skilled and unskilled leisure	0.5
Elasticity of substitution between aggregate non-energy goods and a composite of energy goods	0.4
Elasticity of substitution between different non-energy goods	1.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	1.0
Intertemporal elasticity of substitution	0.5
Government consumption	
Elasticity of substitution between different non-energy goods and a composite of energy goods	0.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6

[a] The input elasticity values apply to the "putty" part of the partial putty-clay production function specification. The corresponding values for the "clay" part are all equal to zero except the Armington elasticities, which are equal to the same values as the "putty" part.
[b] 0.58 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.62 in paper and pulp. 0.76 in food and textile. 0.85 in chemical. 0.87 in transport. 0.92 in steel and metal. 0.94 in mining.
[c] 0.17 in steel and metal. 0.31 in transport. 0.49 in chemical. 0.75 in food and textile. 0.87 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.91 in paper and pulp. 0.98 in mining.
[d] Equal in production and consumption.

The model simulations to be discussed in the following sections all span over 50 years and are based on the following set of assumptions.

(i) Aggregate effective labor stock grows at an annual rate of 1.8 percent, and capital depreciates at an annual rate of 4 percent. Together with the benchmark data, these assumptions yield an interest rate of approximately 5 percent.

(ii) Foreign deposition remains constant at the benchmark level for all pollutants during the entire simulated period.[15,16]

(iii) The (costless) progress in end-of-pipe abatement technology in Sweden results in 0.8 percent emission efficiency improvement annually for SO_2 and 0.5 percent annually for NO_X. This leads to an annual increase in domestic emissions of SO_2 and NO_x of approximately 1 and 1.3 percent respectively, along the reference path. Note that this technological change is policy unrelated.

[15] This assumption is due to the substitution from coal and oil based electricity production towards natural gas based production that takes place in European countries outside Sweden. This, together with abatement policies and progress in abatement technology, is likely to restrain emissions from increasing, despite economic growth.
[16] In the policy simulations (subsection 3.2) of an "international" scenario, foreign emissions are, however, assumed to follow other paths based on domestic emission reductions.

(iv) In all simulations, the government is assumed to adjust the payroll tax to fulfill its intertemporal budget constraint.

3. Simulation results

Having extended the core model to incorporate feedback mechanisms, two new types of issues can be elucidated. The first is related to long term economic projections, more precisely to the question of whether neglect of environmental feedbacks tends to significantly bias projections of the long-term development of real national output and rates of output in major sectors of the economy. The methodology of estimating these feedback effects is to compare an environmentally (and resource) unconstrained steady state projection of the economy, where the availability of primary resources are unaffected by changes in pollution levels, with an environmentally constrained "true" projection of the economy, i.e. a projection where pollution affects primary resources in accordance with the model assumptions. The estimated value will also include the value of environmental resources not captured in market transactions. Thus, this estimated bias is the growth difference of the environmentally unconstrained and the "true" constrained economy, which resembles what Nordhaus (1992) defines as "environmental drag" on economic growth.[17] In addition, the model quantifies the direct and indirect effects on aggregate welfare from pollution flow and accumulation.

The second issue is related to the economic evaluation of environmental policies. If neither the productivity effects nor the direct welfare effects of pollution are taken into account, environmental policies aimed at reducing pollution are likely to reduce national income and welfare. Within the framework of the model presented here, however, environmental policies produce benefits in the form of increased natural resource availability and labor productivity, as well as reduced capital depreciation rate and decreased spending on defensive activities. Thus, it is possible to estimate a measure of net benefit (net cost) of different environmental policy options. The cost of the policy scenarios is quantified by comparing the unconstrained steady state projection with an environmentally constrained projection that includes the environmental policy-induced effects.

Finally, it is important to stress that the assumption concerning the development of imported emissions is significant for the magnitude of many of the feedback effects

[17] Nordhaus (1992, p.29) defines the environmental drag as the reduction in true national output when resources are constrained by pollution, relative a case where resources are superabundant (but not necessarily free). True national output is real national output including appropriate measured consumption, plus the value of net accumulation of all capital.

included.[18] Assuming that emission reductions are unilateral or multilateral pursuits will, in the model, not affect the gross cost (excluding environmental feedbacks), but might strongly affect the feedback effects.

3.1 Long-term projections

Due to the environmental feedbacks, economic growth will be reduced over the simulated time period relative to the unconstrained benchline growth projection. That is, the environmentally constrained feedback model will, in relation to the unconstrained "core" model, produce a lower (average) growth rate over the model horizon. This growth reduction can be divided into reduction due to feedbacks on production, and reduction due to feedbacks on "recreational" value of natural resource services. The former reduction is defined as the reduced (market) value of primary factors, i.e. a reduction in GDP, and the latter, here denoted EGDP, as the reduction of primary factor value including the reduction in (non-market) recreational value. Note that the GDP measure includes the value added from the defensive liming in forests, and also the value of the forest resource used in production, which is partly "produced" by the liming activity.

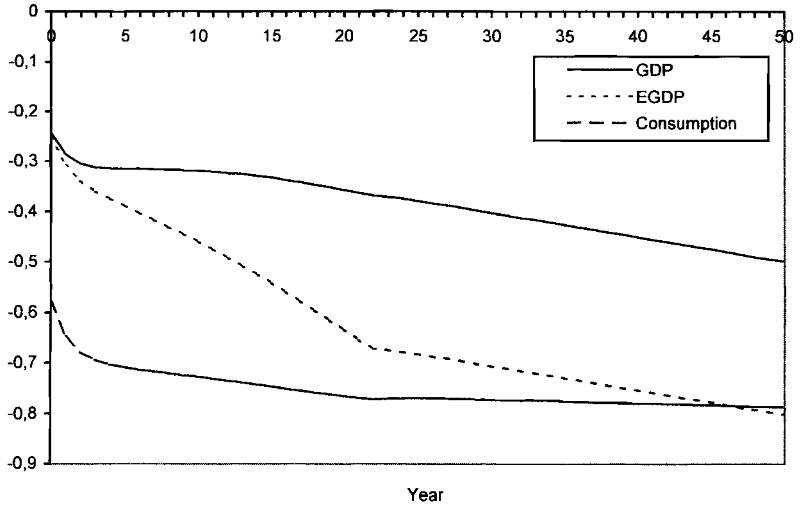
The impact of feedbacks on both GDP and EGDP, as well as on private full consumption value (including leisure) is presented in Figure 3.1. It is obvious that the feedback effects incorporated in the model do not fundamentally change the trends of the long-term macroeconomic development. In terms of average annual rates of growth over the entire 50 year period, the impact of feedback effects is quite small. Yet, the results suggest that emission and accumulation of pollutants in the environment might have a non-negligible economic impact, both in terms of macroeconomic indicators such as GDP and consumption, and in terms of the sectoral structure of the economy.

As shown in Table 3.1, disregarding direct feedback effects, the GDP in the final period is reduced by 0.50 percent relative to GDP in the unconstrained model. The average GDP reduction over the simulated 50 years is 0.38 percent. If the direct feedback effects are included, the corresponding values are 0.80 and 0.62. Relative to the reference path, both GDP and consumption decrease over time when the pollution flow and accumulation increase, although at a relatively slow rate. The relatively flat consumption path stems from the forward-looking consumer's wish to smooth consumption intertemporally.

[18] In the benchmark year, approximately 75 percent of the nitrogen deposition and 80 percent of the sulfur deposition in Sweden were "imported".

The initial decrease in GDP is to a large extent due to the model's equal yield construction. Recall that, to facilitate welfare comparison of the two models, government provision of public goods (excluding liming of lakes) is kept at the environmentally unconstrained reference level in the feedback simulations. This necessitates a relative increase in the payroll tax rate in the feedback model. This is due to the decreased tax revenue that stems from decreased economic activity, as well as the need for additional tax revenues to finance increased defensive spending on acidified lakes. As described in the previous section, the government fulfills the budget constraint by proportionally scaling up the tax rate in *each* period over the simulated horizon, which affects GDP in the early time periods although the environmental damage is then small. The effect on EGDP includes the negative impact on the recreational valuation of the affected resources, and will therefore be relatively larger than the effect on GDP. The use of defensive expenditure in the forest (discussed below) will affect this valuation and consequently, reduce the difference between the two measures. This causes the reduced reduction rate in EGDP shown in Figure 3.1.

Figure 3.1 GDP, EGDP and consumption paths. Percentage difference between feedback model and unconstrained model



Along the reference path, the deposition of sulfur and nitrogen exceeds the assimilating capacity of forest land. Consequently, the accumulation of pollutants in this receptor will increase over time. Being at the forest's maximum carrying capacity (threshold value) at the benchmark therefore implies that forest growth, and thus the annual supply of round-wood, will decline over the whole period if no defensive measures are used. The growth damage in the immediate future will, however, not be sufficiently large for liming to be profitable for the forest owners. However, the value of round-wood increases when damages continue to reduce the annual supply. After 15 years, the annual supply reduction (relative to the reference case) is approximately 14 percent. In year 23, the use of liming becomes profitable and is therefore "activated", resulting in a stabilized supply reduction at approximately 21 percent. The output level of the constant returns defensive activity will consequently increase as pollution accumulation and forest damage increases over time.

The NO_x emission flow from domestic transportation follows a steady increase as the economy grows. With a damage function lacking an upper bound, labor productivity will follow a steady decrease relative to the benchline level. This results in a relative reduction of the effective labor endowment of 0.22 percent in the final year. It is, however, difficult to identify any large sector-specific impact of this, comparatively modest, reduction.

Increased emission and deposition augment the capital stock depreciation rate. Relative to the benchmark damage, estimated to be around 1.9 billion SEK, the corrosive damage increases by 17 percent in the final year. The investment activity increases slightly due to the increased depreciation which, in turn, results in a small increase in the output from the construction and manufacturing sectors that are the major inputs into the investment activity. The aggregate capital stock will, however, decrease slightly due to the increased depreciation, but the effect is less than 0.004 percent of the unconstrained model capital stock.

The impact of the changes in natural resource supply on output differs across sectors. Not surprisingly, the largest output reduction due to environmental damages will take place in the forest sector and closely related sectors, such as the paper and pulp industry. Although forest harvest decreases with 21 percent, the relative output reduction in the forest sector will stabilize at around 17 percent due to the substitution of the natural resource input for labor, capital and energy inputs. The paper and pulp sector, analogously, substitute toward imported forest products, energy and other primary factors, and reduces its output by 12 percent. Finally, the export oriented manufacturing and the steel sectors expand somewhat when forest related industries contract. This expansion could, at least partly, be explained by the assumed balance of payments constraint, which implies that the export from some sectors will increase to "counteract" the decrease in forest related export.

The direct effect on forest recreation value follows, by assumption, the same path as the round-wood supply. This implies a steady decrease in recreational value until year 23 when liming is initiated and a steady (lower) level thereafter. The use of defensive lake liming increases with accumulated forest acidification, but level off when the forest liming becomes profitable. That is, the provision of the public good “lake liming” increases with acidification, but the increase will cease when forest owners start to use defensive measures, which has a positive (external) effect on lakes.

The GDP and EGDP are inaccurate measures of welfare. A better measure is the Hicksian equivalent variation in income (EV), which may here be interpreted as the consumer’s willingness to pay to avoid all feedback effects present in the model. Two EV measures are presented in Table 3.1. The first reflects the indirect effects, i.e. excluding the effects on (separable) consumer recreational valuation, while the second includes both direct and indirect effects. Measured relative to the representative consumer’s present value of income in the unconstrained model, the EV is -1.01 percent and -0.74 percent with and without recreational value, respectively. It is, however, difficult to identify the welfare impact of each feedback effect separately because of their interrelationships. Although slightly incorrect, running the model with one feedback effect at a time indicates that forest damage creates the largest welfare loss, especially if recreational valuation is accounted for. Acidification of lakes is also relatively costly to counteract, while labor and corrosion effects are less costly.

Table 3.1 Summary of environmental feedback impact on welfare and economic growth.

Welfare effect including separable recreational valuation (% EV)	-1.014
Welfare effect excluding recreational valuation (% EV)	-0.744
Average impact on GDP (%)	-0.385
Average impact on EGDP[a] (%)	-0.621
Final year impact on GDP (%)	-0.500
Final year impact on EGDP[a] (%)	-0.802

[a)] The reference value for EGDP includes recreational (non-market) valuation of natural resources.

3.2 Policy evaluation

The estimated welfare impact and the environmental bias in the unconstrained projection from the previous section indicate how costly the negative environmental effects will be in a “business as usual” (BAU) scenario, where no environmental policy (besides liming of lakes) is used. From a policy perspective, it is interesting to compare these costs with the cost from an environmental policy mitigating these effects. In an integrated framework, the model at hand is capable of elucidating both the cost and benefits of a policy, contrary to what is usually the case in applied general equilibrium studies. For example, in the case of a revenue neutral fossil fuel tax policy, the computation endogenously accounts for positive or negative effects due to differences in marginal excess burdens between fossil fuel taxes and the payroll tax (i.e. the "replacement tax"). Among other general equilibrium effects, the model also captures policy-induced changes in the use of real resources for defensive purposes and the effect on primary factor endowment.

A simple, but relatively realistic, policy scenario is simulated to assess the cost and benefits from a policy aiming at reducing negative effects from NO_x and SO_2 emissions in Sweden. The policy objective is to reduce damage from acidification by imposing a revenue neutral ad valorem tax on fossil fuel based on the (average) emission of acidifying substances originating from combustion of the fuel type.[19] The tax is introduced in the benchmark year and remains throughout the simulated horizon. Two different assumptions concerning foreign emissions imported to Sweden are used. Either the policy is strictly unilateral, which implies that the foreign emissions remain at the benchmark level, or the policy is part of an international pursuit, which implies that foreign emissions (approximately) follow the same proportional reduction as domestic emissions.[20] The two different scenarios will be referred to as the *unilateral* and *international* policy, respectively. The policy experiment is simulated using the core model and the feedback model. This enables evaluation if the inclusion of feedback will change the policy recommendation in any significant way. For each scenario, the simulation is carried out using three different tax levels referred to as low, medium and high tax level, respectively.[21]

Table 3.2 summarizes the key results. Not surprisingly, the tax policy reduces welfare in the core model simulations. That is, "substituting" the fuel taxes for payroll taxes decreases welfare by 0.037 percent for the low tax policy, and up to 0.233 percent for the high tax policy relative to the reference path present value income (including the value of recreational activities). Clearly, with no environmental feedbacks included in the core model, the effects are identical in the unilateral and the international policy scenarios because the foreign emission reduction has no effect on the economy in this model.

[19] The tax is hence based on a weighted average of each fuel type's average emission of NO_x and SO_2. This is evidently not a "perfect" emission tax due to, among other things, the inequality in emission factors between users. It is, however, likely to be an administratively less costly tax relatively to a "perfect" user specific tax.

[20] Note that the model is unable to simulate any, potentially important, changes in terms of trade that would be the result of an international pursuit.

[21] As a reference, the low level corresponds to a tax level of approximately 10 percent on heavy fuel oil net value, with proportional tax on the other fuels based on their relative average emission factors. The medium and high levels are 3 and 6 times the low level, respectively.

Projecting the economy with feedbacks *and* tax policy creates a larger welfare loss than the projection without policy, i.e. the cost of the tax exceeds the benefit of reduced pollution damage. Although the deposition of foreign emission is reduced at no additional cost in the "international" scenario, the policy is still not welfare improving. The cost of the "international" low tax policy is, however, close to zero. It should be noted that the emission reduction in this "low tax" scenario is very low, less than 4 percent. Hence, as the net cost of the policy increases with increased emission reduction, it is clear that any emission reduction with a fossil fuel tax is unlikely to be beneficial if the policy goal is to reduce the damage effects considered in the model.

Table 3.2 Impact on welfare and GDP of environmental tax policy.

	Core model			Feedback model		
	Tax level[a]			Tax level[a]		
	Low	Medium	High	Low	Medium	High
Unilateral policy:						
Welfare (% EV)[b]	-0.037	-0.113	-0.233	-0.029	-0.092	-0.194
Welfare (% EV excluding recreational valuation)[c]	-0.037	-0.115	-0.237	-0.031	-0.097	-0.204
"International" policy:						
Welfare (% EV)[b]	-0.037	-0.113	-0.233	-0.003	-0.033	-0.086
Welfare (% EV excluding recreational valuation)[c]	-0.037	-0.115	-0.237	-0.013	-0.046	-0.111

a) The low level corresponds to an ad valorem tax level of approximately 10 percent on heavy fuel oil, with proportional tax on the other fuels based on their relative average emission factors. The medium and high levels are 3 times and 6 times the low level, respectively.

b) Percent Hicksian EV in relation to BAU present value of consumption including recreational valuation.

c) Percent Hicksian EV in relation to BAU present value of consumption excluding recreational valuation.

3.3 Sensitivity analysis

The results presented above are based on point estimates of environmental damage parameters. None of the studies on which the numbers are based presents a probability distribution for these parameters. Therefore, the sensitivity analysis with respect to these values will be accomplished by simply scaling the marginal damage estimates.

The simulation results are shown in Table 3.3 below. The welfare effect of a 50 percent increase in marginal damage in all feedback effects considered raises the welfare cost by about 30 percent. As has been noted in the previous section, the possibility to counteract forest acidification with defensive expenditures (liming) may produce negative side effects.

Therefore, liming may not be a long-term solution to the acidification problem.[22] To evaluate the effects of the inability to counteract the acidification damage in the forest, simulations are undertaken without the forest liming possibility. The results indicate that the welfare effect will increase by about 30 percent. Assuming both higher marginal damage and no forest liming produces substantially higher welfare cost. This large effect is partly a result of the (assumed) constant marginal damage that could be questionable for large damage effects. A concave damage function might be a better approximation.

Several key parameters can be considered important for the sensitivity of the policy results. For example, the cost of fossil fuel - payroll tax reform depends on energy-energy and the energy-capital substitution elasticity, as well as the labor supply elasticity and intertemporal substitution elasticity. Running the model with different plausible values of these elasticities indicates that the results are relatively robust to changes in these parameters. Higher elasticity of substitution among energy goods, and between energy and capital, *increase* the welfare cost of the policy due to a larger excess burden for a given level of fossil fuel tax. Higher elasticity values will, on the other hand, result in more abatement and, thus, have a larger positive effect on the environment for a given tax level. The overall impact of both these effects is, however, that the welfare cost of the policy increases with the elasticity values.

The effect of changes in labor supply elasticity or in the intertemporal elasticity of substitution depends, among other things, on the incidence of the fossil fuel tax. That is, if the tax falls primarily on private consumption and therefore reduces real income, or on capital and therefore affects the saving decision. Scaling these elasticities up and down in the model indicates, however, that the effects on the policy outcome are very small. Higher labor supply elasticity increases the welfare cost of the policy, while changing the intertemporal substitution elasticity has no noticeable effect on welfare.

Clearly, the policy conclusions are sensitive to the marginal damage numbers, and to the possibility to counteract forest damage. Evidently, an environmental policy can be justified by sufficiently scaling up the damage parameters in the model. As is shown in Table 3.3, all three "international" policies are welfare improving if the possibility to counteract the forest land acidification is unavailable. The availability of counteracting measures for the forest land acidification is hence very important for the policy conclusion as it affects both the forest damage and the need for the government to counteract the lake acidification. The use of a medium or a high fossil fuel tax cannot be motivated by the 50 percent increase in marginal

[22] It should be noted, however, that liming might be more effective in mitigating damages than indicated by the model specification used above, in which liming only mitigates damages in one period.

damage if the damage can be offset by liming. These results emphasize the importance to consider the possibility to counteract damages with other measures than the use of fossil fuel taxes, as well as to consider the coordination between the defensive measures.

Table 3.3 Sensitivity analysis of long-term projections and policy results.

	Base case marginal damage	Base case marginal damage without defensive forest activity	50 % increase in marginal damage	50 % increase in marginal damage without defensive forest activity
BAU effects of feedbacks:				
Welfare (% EV)[a]	-1.014	-1.306	-1.353	-2.155
Welfare (% EV excluding recreational valuation)[b]	-0.744	-0.881	-1.063	-1.523
Average impact on GDP	-0.385	-0.525	-0.608	-0.989
Average impact on EGDP	-0.621	-0.873	-0.857	-1.507
Final year impact on GDP	-0.500	-0.830	-0.819	-1.620
Final year impact on EGDP	-0.802	-1.534	-1.106	-2.668
Policy Evaluation,				
"International" policy scenario: [c]				
Low tax: Welfare (% EV)[a]	-0.003	0.016	0.002	0.050
Medium tax: Welfare (% EV)[a]	-0.033	0.033	-0.018	0.125
High tax: Welfare (% EV)[a]	-0.086	0.029	-0.072	0.192

a) Percent Hicksian EV in relation to BAU present value of consumption including recreational valuation.

b) Percent Hicksian EV in relation to BAU present value of consumption excluding recreational valuation.

c) The "low" tax level corresponds to an ad valorem tax level of approximately 10 percent on heavy fuel oil, with proportional tax on the other fuels based on their relative average emission factors. The "medium" and "high" levels are 3 times and 6 times the low level, respectively.

4. Summary and conclusions

Environmental policies should be judged by comparing economic costs with environmental benefits. In a CGE analysis, economic costs and environmental benefits are often treated as separable. Clearly, this approach will not capture the effect which, in most cases, is the reason for modeling environmental problems in the first place, that is, the destruction of resources which constitutes the base in production of goods and services. A more satisfactory way of assessing these issues is to explicitly let changes in environmental quality affect the production possibilities of the economy, i.e. to include bi-directional feedback effects.

There have been some attempts to include these feedback effects in CGE models. The simplest versions of these models use multiplicative specifications of how environmental quality affects output, i.e. environmental quality change is assumed to affect total factor productivity. In most cases this approach is unrealistic as it abstracts from the possibility to substitute away from affected resources. Another, and probably more realistic, way to model these effects is to include the use of the affected resources in the model, and link the externality to these endowments in a way consistent with results from, for example, ecological models. Furthermore, there are often other means of reducing environmental damage than to abate emissions. Such "defensive activities" use real resources that can be used to produce goods and services elsewhere, and should therefore be explicitly included in the model.

The latter approach is the one applied in the present study. By using a multi-sectoral dynamic CGE model of Sweden that includes several potentially important environmental feedback mechanisms due to emission of acidifying substances, the effects on economic growth and welfare and the cost and benefit of environmental policy are assessed. The feedback mechanisms are based on relatively rough estimates, which, however, reflect the current status of the economic-environmental accounts of Sweden. Before interpreting the results it must be emphasized that some of the figures are very tentative and that some possibly important effects are not included in the calculations.

Subject to these reservations, the simulation results suggest that increased emissions of acidifying pollutants, NO_x and SO_2, over the next few decades will have a non-negligible negative impact on primary factors, thereby leading to a noticeable impact on Swedish GDP. However, in terms of the overall rate and pattern of economic growth, numerical CGE models with and without endogenous feedback effects from these pollutants produce very similar results.

When evaluating environmental policy, the results indicate that positive environmental effects of emission reductions are smaller than the costs of attaining these emission reductions by means of a revenue neutral fossil fuel tax. Clearly, due to the large emission "imported" into Sweden, policy benefits are highly dependent on whether the policy is a unilateral pursuit or the result of an international agreement also involving reductions in neighboring countries. However, assuming proportional emission reductions from foreign sources, as if the policy would be part of an international agreement, do not justify the fossil fuel tax policy. Important assumptions underlying these results are the availability of other defensive measures to counteract the damages.

This study should be viewed as a first step towards a model of the Swedish economic-environmental interactions. Additional research, especially on the data side, is needed to enable a better basis for modeling of environmental feedbacks. To provide the means necessary to relax the assumption of separability between consumption of goods and environment in the utility function, the nature of household demand for environmental services must be further explored.

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Chapter V

A Dynamic Computable General Equilibrium Model for Environmental Policy Analysis

1. Introduction

This paper presents and discusses the structure and calibration of a dynamic multi-sector computable general equilibrium model of Sweden.[1] The purpose is to provide technical details of the model to aid the interpretation of results from policy simulations undertaken in chapters III and IV.[2] In addition to the equations of the model, an overview of benchmark data and parameter values is included. Simulations are also performed to examine the model's sensitivity to different assumptions concerning model structure and to the exogenous parameter values. The model is primarily constructed for environmental policy related analysis, and the model dimension is therefore limited by the availability of reliable emission data. The data allow for a disaggregation level with 17 producing industries, 19 goods, one government consumer, one representative private consumer, and three main pollutants. Primary factors consist of two types of labor, sector-specific and intersectorally mobile capital, and natural resources. All major taxes are represented in the model, with an emphasis on the energy and environmental tax system.

Conceptually, the model is an Arrow-Debreau model with complete markets and no money. It is fully dynamic in the sense that the representative consumer has perfect foresight, and optimally allocates consumption and savings over the infinite horizon, subject to an intertemporal budget constraint. A partial "putty-clay" assumption is built into the model to impose adjustment cost. Sweden is regarded as a small open economy and trade with the "rest of the world" is subject to a balance constraint ensuring an intertemporal balance of payment.

The outline of the rest of this paper is as follows. The next section presents the structure of production and consumption functions, followed by derivation of the equilibrium conditions. Calibration issues and additional model constraints are also discussed. The third section

[1] The model code in GAMS/MPSGE programming language (Brooke et al. (1992), Rutherford (1999)) is available from the author upon request.
[2] Note that the notation used in this chapter might differ slightly from the notation used in chapter III and IV.

briefly discusses the benchmark data and choice of exogenous parameters. In section 4, policy simulations are undertaken to assess the sensitivity to some of the model assumptions. The final section contains some concluding remarks.

2. The core model

2.1 Index sets

To make the model description tractable it is helpful to start by defining the index sets. The sets and indices used are presented in Table 2.1. The domestic producers are numbered S1 to S17, corresponding to the 17 sectors in Table 2.2, and goods for final and intermediate demand are numbered G1 to G19, corresponding to the 19 commodities presented in Table 2.3. Note that the model name for sectors and goods are the same although, for most goods, there is no one to one correspondence between them in the model.

Table 2.1 Sets and indices description

Index sets and indices		Description
Sets		
	FD	Goods for final and intermediate demand {G1,...,G19}
	EN	Energy goods {G15,G16,...,G19}
	NE	Non-energy goods {G1,...,G14}
	PE	Polluting energy goods {G16,...,G19}
	EP	Goods produced by the petroleum and mining sectors {G14,G16,G17,G18}
	NPE	Non-polluting energy goods {G15}
	PF	Primary factors $\{LS,LU,NR,K,IK_1,IK_2,...,IK_{17}\}$
	DP	Domestic producers {S1,...,S17}
	CONS	Consumers {*RA*,*GVT*}
	POLL	Pollutants $\{CO_2,SO_2,NO_x\}$
Index		
	i	Goods
	j	Domestic producers
	q	Domestic producers and consumers
	l	Labor types
	t	Time periods
	h	Pollutants

Table 2.2 Domestic production sectors

Sector	SNR Code[a]	Model name
S1	1100	Agriculture
S2	1200	Forestry
S3	1300	Fishing
S4	31-3300, 3600	Food and Textile
S5	3400	Pulp and Paper
S6	3500 (Exl. 3531)	Chemical
S7	3700	Steel and metal
S8	3800, 3900	Manufacturing
S9	4300	Water and Sewage
S10	5000	Construction
S11	7100	Transport
S12	6000, 7200, 8000 (Exl. 8310)	Trade and Services
S13	8310	Dwelling
S14	4100	Electricity and Heating
S15	4200	Gas
S16	3531	Petroleum
S17	2000	Mining

[a] Sector code in Swedish National Accounts.

Table 2.3 Goods

Goods	Model name
G1	Agriculture
G2	Forestry
G3	Fishing
G4	Food and Textile
G5	Pulp and Paper
G6	Chemical
G7	Steel and Metal
G8	Manufacturing
G9	Water and Sewage
G10	Construction
G11	Transport
G12	Trade and Services
G13	Dwelling
G14	Other mining products
G15	Electricity and Heating
G16	Coal and Coke
G17	Heavy fuel oil
G18	Other petroleum fuels
G19	Gas

2.2 Production structure

Production in all sectors is represented by nested constant elasticity of substitution (CES) functions. In order to take capital adjustment costs into account, a partial putty-clay specification[3] is used. This means that each sector's output is represented by the sum of the output from two production technologies, a "malleable capital technology" and a "non-malleable capital technology". For the malleable capital production, the sector-specific output is given by[4]

$$Y_j^m = \min\left[\frac{VE_j}{a_{jVE}}, \left\{\frac{A_{ji}}{a_{ji}}\right\}_{i\in\{G1,..,G14|a_{ji}>0\}}\right], \qquad \forall j \tag{1}$$

where Y_j^m is the output, A_{ji} is industry j's use of input i, and a_{ji} are share parameters.[5] VE_j is a CES nest of intermediate energy inputs and primary factors

$$VE_j = B_{jVE}\left(\gamma_{jL}^{1/\sigma_{jLK}} L_j^{(\sigma_{jLK}-1)/\sigma_{jLK}} + \gamma_{jKNE}^{1/\sigma_{jLK}} KNE_j^{(\sigma_{jLK}-1)/\sigma_{jLK}}\right)^{\sigma_{jLK}/(\sigma_{jLK}-1)}, \tag{2}$$

where L_j, in turn, is a CES aggregate of skilled and unskilled labor

$$L_j = B_{jL}\left(\gamma_{jLS}^{1/\sigma_{jL}} LS_j^{(\sigma_{jL}-1)/\sigma_L} + \gamma_{jLU}^{1/\sigma_{jL}} LU_j^{(\sigma_{jL}-1)/\sigma_L}\right)^{\sigma_{jL}/(\sigma_{jL}-1)}, \tag{3}$$

and KNE_j is a CES aggregate of malleable capital, natural resources and energy

$$KNE_j = B_{jKNE}\left(\gamma_{jKN}^{1/\sigma_{jKE}} KN_j^{(\sigma_{jke}-1)/\sigma_{jke}} + \gamma_{jE}^{1/\sigma_{jKE}} E_j^{(\sigma_{jke}-1)/\sigma_{jke}}\right)^{\sigma_{jke}/(\sigma_{jke}-1)}. \tag{4}$$

At the final level, if the sector utilizes natural resources[6], capital-natural resource and energy substitutions are given by

$$KN_j = B_{jKN}\left(\gamma_{jKN}^{1/\sigma_{jKN}} K_j^{(\sigma_{jKN}-1)/\sigma_{jKN}} + \gamma_{NR}^{1/\sigma_{jKN}} NR_j^{(\sigma_{jKN}-1)/\sigma_{jKN}}\right)^{\sigma_{JKN}/(\sigma_{jKN}-1)} \tag{5}$$

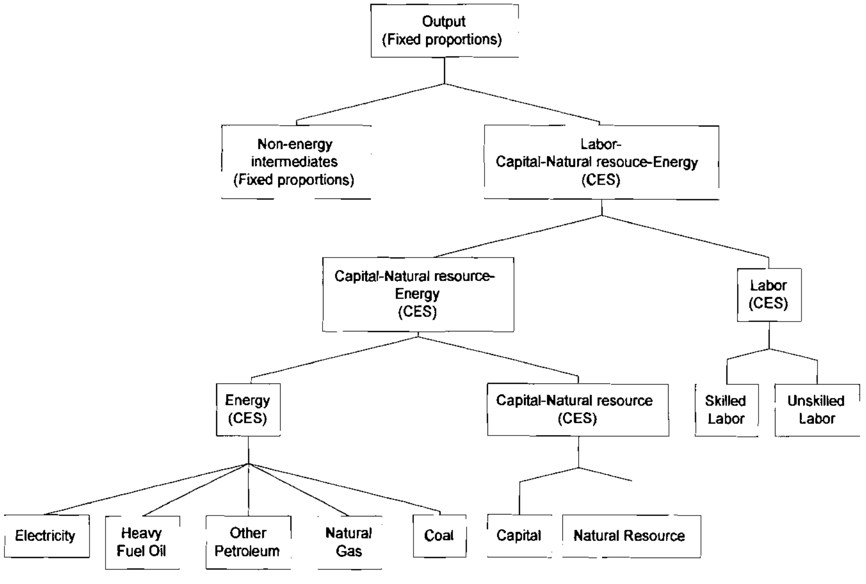
and

$$E_j = B_{jE}\left(\sum_{i\in EN}\gamma_{ji}^{1/\sigma_{jE}} A_{ji}^{(\sigma_{jE}-1)/\sigma_{jE}}\right)^{\sigma_{jE}/(\sigma_{jE}-1)}, \tag{6}$$

[3] See e.g. Phelps (1963).
[4] In order to simplify notation, time indices are omitted in the equations that are strictly intratemporal.
[5] A list of variable and parameter names is presented in the end of this section.
[6] In the version of the model used in this thesis, only sector S2 uses natural resources.

respectively. The B:s and γ:s in equations (2) to (6) are scaling and share parameters. The σ:s are the elasticities of substitution that are all greater than zero, thereby reflecting a higher degree of substitutability between primary factors and between different types of energy goods in the lower nests. The nesting structure described above is illustrated in Figure 2.1.[7]

Figure 2.1 Production nesting structure



The non-malleable capital production technology lacks substitution possibilities at all levels, and is hence represented by a single-level Leontief function

$$Y_j^{nm} = \min\left[\left. \frac{LU_j}{a_{jLU}}, \frac{LS_j}{a_{jLS}}, \frac{IK_j}{a_{jIK}}, \frac{NR_j}{a_{jNR}} \right|_{a_{jNR}>0}, \left\{ \frac{A_{ji}}{a_{ji}} \right\}_{i \in \{G1,..,G19 | a_{ji}>0\}} \right], \qquad \forall j \qquad (7)$$

where the input value shares, a_j, correspond to the benchmark shares in the production using malleable capital. However, here the sector-specific capital, IK_j, is used in place of malleable capital, K_j.

[7] The nesting structure used here is relatively common in CGE models used for energy-environmental related policy evaluations, and is the structure proposed by, for example, Burniaux et al. (1991) and Kemfert and Welch (1997). Another plausible nesting structure is discussed and explored in section 4.

Finally, sector j's total output consists of the sum of the output from the two technologies, i.e.

$$Y_j = Y_j^m + Y_j^{nm}. \tag{8}$$

The industry output, with two exceptions described below, is transformed into domestically produced goods, using a fixed coefficient technology. The transformation is hence given by

$$Z_i = \min\left[\left\{\frac{Y_{ij}}{b_{ij}}\right\}_{j\in\{S1,\ldots,S15|b_{ij}>0\}}\right], \qquad \forall i \notin EP. \tag{9}$$

Two sectors, S16 and S17, produce outputs that have a one to one relation with the goods, i.e. the outputs from these sectors are not transformed by (9). Moreover, each of these sectors produces joint outputs according to a constant elasticity of transformation (CET) frontier. That is, for the petroleum industry, S16,

$$Y_{S16} = B_{S16}\left(\alpha_{G17}^{1/\varepsilon_{S16}} Z_{G17}^{(\varepsilon_{S16}-1)/\varepsilon_{S16}} + \alpha_{G18}^{1/\varepsilon_{S16}} Z_{G18}^{(\varepsilon_{S16}-1)/\varepsilon_{S16}}\right)^{\varepsilon_{S16}/(\varepsilon_{S16}-1)}, \tag{10}$$

where ε is the elasticity of transformation and B and α are scaling and share parameters. An analogous function describes the joint output in the mining sector, S17, producing goods Z_{G14} and Z_{G16}.[8]

The goods, Z_i, are, in turn, transformed into goods destined for the domestic market, D_i and goods destined for the export market, X_i. This transformation is described by the CET function

$$Z_i = B_{iX}\left(\alpha_{iD}^{1/\varepsilon_{iD}} D_i^{(\varepsilon_{iD}-1)/\varepsilon_{iD}} + \alpha_{iX}^{1/\varepsilon_{iD}} X_i^{(\varepsilon_{iD}-1)/\varepsilon_{iD}}\right)^{\varepsilon_{iD}/(\varepsilon_{iD}-1)}. \tag{11}$$

These transformation relations can be interpreted as differences in the technical processes associated with the production of the different outputs. High elasticity of transformation, i.e. a high ε, indicates that the outputs are relatively homogenous, and vice versa.

The goods for intermediate and final consumption are defined as composite commodities "produced" from foreign and domestic goods. Due to data limitations, all producers and

[8] This specification is used to facilitate the separation of energy goods with different emission characteristics. Although input data are available for these energy goods, there is a lack of specific production data.

consumers are assumed to have identical preferences over foreign and domestic varieties of each particular commodity. The foreign and domestic varieties are regarded as imperfect substitutes in accordance with the so-called Armington approach (Armington, 1969). For "Armington commodity" i, the "production function" for composite good A_i, in terms of domestic output D_i and imported good M_i, is given by the CES function

$$A_i = B_{iA}\left(\gamma_{iD}^{1/\sigma_{iA}} D_i^{(\sigma_{iA}-1)/\sigma_{iA}} + \gamma_{iD}^{1/\sigma_{iA}} M_i^{(\sigma_{iA}-1)/\sigma}\right)^{\sigma_{iA}/(\sigma_{iA}-1)}. \tag{12}$$

Note that this formulation implies that for sectors S1 and S2, for example, the input of Armington good i, A_{1i} and A_{2i} respectively, will consist of the same proportions of imported and domestically produced goods. However, it does not imply that sectors 1 and 2 demand the same amount of A_i, or that the import and domestic proportions of good i are constant.

2.3 Capital formation

The model includes 17 sector-specific capital stocks and one perfectly malleable capital stock. The amount of sector-specific capital is given in the benchmark period and this capital stock changes according to an identical geometric depreciation rate, i.e. for each sector j,

$$IK_{jt+1} = (1-\delta_K)IK_{jt} \qquad\qquad IK_{j0} = \overline{IK}_{j0}. \tag{13}$$

The malleable capital stock K is produced using intermediate goods according to the fixed proportion capital formation function

$$I = \min\left[\left\{\frac{A_{Ii}}{a_{Ii}}\right\}_{i\in\{G1,..,G19|a_{Ii}>0\}}\right], \tag{14}$$

and depreciates according to a geometric depreciation rate, δ_K. That is, with an assumed investment lag of one period, the capital stock evolves according to

$$K_{t+1} = (1-\delta_K)K_t - I_t\,, \qquad\qquad K_0 = \overline{K}_0. \tag{15}$$

This capital specification implies that a larger share of malleable capital will be used in the long run. Together with the putty-clay specification (equations (1) to (8)) this, in turn, yields relatively higher (energy) price responsiveness in the long run, which is in accordance with empirical observations.[9]

In addition to the capital goods above, there is (sector-specific) natural resource capital that is endowed to the economy at an exogenously determined amount, i.e. the natural resource services available at time t is simply

$$NR_{jt} = \overline{NR}_{jt}. \tag{16}$$

2.4 Private consumer utility and income

The private consumer is modeled as a representative agent with a utility function separable over both time and commodity groups. This representative agent consumes goods, services and leisure according to a nested CES function. In every period the representative agent's utility from this (full) consumption, or equivalently, the aggregate quantity of the composite consumption good is given by

$$C = \left(\gamma_{GS}^{1/\sigma_{CL}} GS^{(\sigma_{CL}-1)/\sigma_{CL}} + \gamma_{L_{RA}}^{1/\sigma_{CL}} L_{RA}^{(\sigma_{CL}-1)/\sigma_{CL}}\right)^{\sigma_{CL}/(\sigma_{CL}-1)}, \tag{17}$$

where leisure could be chosen to be of "skilled" or "unskilled" type according to

$$L_{RA} = \left(\gamma_{CLS}^{1/\sigma_L} LS_{RA}^{(\sigma_L-1)/\sigma_L} + \gamma_{L_{LU}}^{1/\sigma_L} LU_{RA}^{(\sigma_L-1)/\sigma_L}\right)^{\sigma_L/(\sigma_L-1)}. \tag{18}$$

To reflect differences in substitutability, goods and service consumption is divided into energy, EG, and non-energy consumption, NEG, given by

$$GS = \left(\gamma_{NEG}^{1/\sigma_{GS}} NEG^{(\sigma_{GS}-1)/\sigma_{GS}} + \gamma_{EG}^{1/\sigma_{GS}} EG^{(\sigma_{GS}-1)/\sigma_{GS}}\right)^{\sigma_{GS}/(\sigma_{GS}-1)}, \tag{19}$$

which, finally, are CES functions of Armington energy goods,

$$EG = \left(\sum_{i\in EN} \gamma_{CEi}^{1/\sigma_{CE}} A_{RAi}^{(\sigma_{CE}-1)/\sigma_{CE}}\right)^{\sigma_{CE}/(\sigma_{CE}-1)}, \tag{20}$$

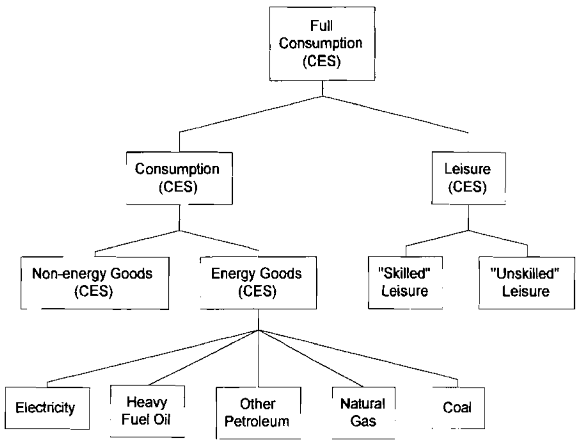
and non-energy goods,

[9] See section 4.

$$NEG = \left(\sum_{i \in NE} \gamma_{CNEi}^{1/\sigma_{CNE}} A_{RAi}^{(\sigma_{CNE}-1)/\sigma_{CNE}} \right)^{\sigma_{CNE}/(\sigma_{CNE}-1)}. \tag{21}$$

The intratemporal nesting structure described by these equations is illustrated in Figure 2.2.

Figure 2.2 Intratemporal consumption nesting structure



The representative agent has perfect foresight and is modeled as an infinitely-lived consumer with an intertemporal utility function given by

$$U(C_t) = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\Delta} \right)^t C_t^{(\sigma_C-1)/\sigma_C} \right]^{\sigma_C/(1-\sigma_C)}, \tag{22}$$

i.e. the intertemporal utility is the discounted sum of intra-period utility from consumption of goods and leisure over the infinite horizon. In (22) the parameters σ_C and Δ are the constant intertemporal elasticity of consumption and the discount rate, respectively.

The consumer is endowed with the labor resources LS_t and LU_t (measured in efficiency units) which, in each time period, are exogenously given by

$$LS_t = \overline{LS}_t, \tag{23}$$

and

$$LU_t = \overline{LU}_t. \tag{24}$$

Furthermore, the consumer is endowed with natural resources, NR_{jt}, and the capital stocks, K_0 and IK_{j0}. In addition to the payments for supplying these factor endowments, the consumer also receive direct transfers from the government. Moreover, it is assumed that the consumer can borrow and lend freely over the model horizon at the domestic interest rate. The present value of the representative agent's wealth over the horizon can be described by

$$INC = P_0^K K_0 + \sum_{t=0}^{\infty} p_t^{LS} LS_t + p_t^{LU} LU_t + \sum_j p_t^{IK_j} IK_{jt} + p_t^{NR_j} NR_{jt} + \theta^{LT} LT_t + BM_t\,, \tag{25}$$

where prices are defined in present value terms. $\theta^{LT}LT_t$ is the present value of transfers from the government and BM_t is the present value net indebtedness with respect to the "rest of the world".

2.5 Government public good provision and income

The model includes a single government that collects revenues from taxes and tariffs, subsidizes production, transfers income to the household, and uses non-energy goods and an energy composite good in fixed proportions. That is, in each period, the government consumption (or public good provision) is described by

$$GOVC = \min\left[\frac{EG_{GVT}}{a_{GVTEG}}, \left\{\frac{A_{GVTi}}{a_{GVTi}}\right\}_{i\in\{G1,..,G14|a_{GVTi}>0\}}\right], \tag{26}$$

where EG is a CES composite of energy goods,

$$EG_{GVT} = \left(\sum_{i\in EN} \gamma_{GVTEi}^{1/\sigma_{GVTE}} A_{GVTi}^{(\sigma_{CE}-1)/\sigma_{GVTE}}\right)^{\sigma_{GVTE}/(\sigma_{GVTE}-1)}. \tag{27}$$

The net tax revenues consist of revenues from ad valorem taxation of final and intermediate use of goods

$$TR^A = \sum_i \sum_q \tau_{qi}^A p_i^A A_{qi}\,, \tag{28}$$

where τ^A consists of sector, consumer and good specific taxes such as electricity, energy and different environmental taxes. Furthermore, tax is also levied on primary factors yielding revenues according to

$$TR^F = \sum_j \tau_j^K \left(p^K K_j + p^{IK_j} IK_j\right) + \tau_j^{LS} p^{LS} LS_j + \tau_j^{LU} p^{LU} LU_j + \tau_j^K p^{NR_j} NR_j \,, \tag{29}$$

where τ^K, τ^{LS} and τ^{LU} are capital, skilled and unskilled labor taxes, respectively. Finally, subsidies on domestic production as well as goods taxes, not included in τ^A, are expressed as a net tax, τ^{DX}, levied on domestically produced goods, and an import tariff, τ^M, levied on imported goods, yielding tax revenues according to

$$TR^{XM} = \sum_i \tau_i^{DX} \left(p_i^D D_i + p_i^X X_i\right) + \tau_i^M p_i^M M_i \,. \tag{30}$$

The government's total tax revenue, *TR*, could hence be expressed as the sum of the above revenues

$$TR = TR^A + TR^F + TR^{XM} \,. \tag{31}$$

2.6 Equilibrium conditions

A solution to the model must satisfy both the intertemporal and general equilibrium conditions simultaneously. The model is formulated as a mixed complementarity problem[10]. The Arrow-Debreu economic equilibrium is formulated[11] as nonlinear inequalities corresponding to zero profit in all constant returns to scale activities, market clearance for all goods and factors, trade balance with the "rest of the world", and income balance for the representative agent and the government. In this formulation, the zero profit condition for an activity is complementary to the activity level, and the market clearance for a commodity or factor is complementary to a commodity or factor price. This implies that all *active* activities make zero profit, and all markets clear for all goods and factors with a *positive* price at every point in time.

[10] See Rutherford (1995).
[11] The GAMS interface for general equilibrium modeling, MPSGE (Rutherford, 1999), is used to generate the model in mixed complementarity format.

Producer behavior

Producers maximize the present value of profits taking prices as given or, equivalently, given the CRS production technology, minimizes the cost of a given production level. Since producers rent the primary factors and have no adjustment cost, and since the sector-specific non-malleable capital is available at a predetermined level in each period, the problem of maximizing the present value of profits is reduced to a problem of maximizing profits in each period, without regard to outcomes in other periods. With the constant return to scale technology represented by the nested CES/CET production function, the input and output decisions are separable as are the input decisions at the different nesting levels. The producers' decisions could hence be decomposed into separate subproblems.

From equation (1) to (6), the resulting per unit profit function for the "malleable capital technology" is the output price minus unit cost, i.e. for all sectors j and in each time period

$$\Pi_j^m = p_j - \sum_{i \in NE} a_{ji} p_i^A \left(1 + \tau_{ji}^A\right) - a_{jVE} p_{jVE}, \tag{32}$$

where the third term on the right-hand side, the composite value added-energy price p_{jVE}, is derived from the second CES nest (2) to be

$$p_{jVE} = \frac{1}{B_{jVE}} \left(\gamma_{jL} p_{jL}^{1-\sigma_{jLK}} + \gamma_{jKNE} p_{jKNE}^{1-\sigma_{jLK}}\right)^{1/(1-\sigma_{jLK})}, \tag{33}$$

and analogous for p_{jL} and p_{jKNE} and all the composite prices corresponding to the deeper CES nests. The intra-period zero-profit condition for sector j specifies $-\Pi_j^m \geq 0$. The associated dual variable to this condition is the activity level Y_j^m, i.e. if the zero-profit condition does not hold, the production Y_j^m will be inactive.

For the part of production using non-malleable capital, the corresponding per unit profit function is

$$\begin{aligned} \Pi_j^{nm} = p_j - \sum_i a_{ji} p_i^A \left(1 + \tau_{ji}^A\right) + \sum_l a_{jl} p_j^l \left(1 + \tau_j^l\right) + \\ a_{jIK} p_j^{IK} \left(1 + \tau_j^K\right) IK_j + a_{jNR} p^{NR_j} \left(1 + \tau_j^K\right) NR_j. \end{aligned} \tag{34}$$

Here, the zero-profit condition $-\Pi_j^{nm} \geq 0$ has the associated dual variable Y_j^{nm}, i.e. the production using non-malleable capital will be inactive unless the zero profit condition holds.

In the sectors with joint output, the choice of produced good is derived from revenue maximization for a given output level, $\overline{Y}$. For sector S16 $\max p^Z_{G17} Z_{G17} + p^Z_{G18} Z_{G18}$ s.t. $Y_{16}(Z_{G17}, Z_{G18}) = \overline{Y}_{16}$ yields an output price described by

$$p_{S16} = \frac{1}{B_{S16}} \left(\alpha_{G17} (p^Z_{G17})^{1-\varepsilon_{S16}} + \alpha_{G18} (p^Z_{G18})^{1-\varepsilon_{S16}} \right)^{1/(1-\varepsilon_{S16})}, \tag{35}$$

and analogously for sector S17 with output G14 and G16.

The output is transformed into goods according to the fixed coefficient function Z activity with the corresponding profit function

$$\Pi^Z_i = p^Z_i - \sum_j b_{ij} p_j, \qquad \forall i \notin EP. \tag{36}$$

The output price is described by

$$p^Z_i = \frac{\left(1 - \tau^{DX}_i\right)}{B_{iX}} \left(\alpha_{iD} (p^D_i)^{1-\varepsilon_{iD}} + \alpha_{iX} (p^X_i)^{1-\varepsilon_{iD}} \right)^{1/(1-\varepsilon_{iD})} \qquad \forall i. \tag{37}$$

The corresponding "zero profit" condition associated with the Z_i activity is $-\Pi^Z_i \geq 0$.

The aggregation of domestic and imported varieties, i.e. the "production" of Armington goods according to (12) has the corresponding per unit profit function

$$\Pi^A_i = p^A_i - \frac{1}{B_{iA}} \left(\gamma_{iD} p_i^{D\,1-\sigma_{iA}} + \gamma_{iM} \left((1 + \tau^M_i) p^M_i \right)^{1-\sigma_{iA}} \right)^{1/(1-\sigma_{iA})} \qquad \forall i, \tag{38}$$

where the zero profit condition $-\Pi^A_j \geq 0$ has the associated dual variable A_i.

Capital formation

In every period *t*, capital formation, i.e. the investment activity (14), has, the corresponding profit function described by

$$\Pi^I_t = P^K_{t+1} - \sum_I a_{Ii} p^A_{it} \left(1 + \tau^A_{Ii}\right). \tag{39}$$

An efficient allocation of investment over time requires that the following intertemporal zero profit condition for capital accumulation hold:

$$P_t^K = p_t^K + (1-\delta_K)P_{t+1}^K. \tag{40}$$

That is, the cost of one unit of capital good (stock), P^K, in period t equals the return to capital, p^K, and the depreciated unit cost of investment. If the cost of new capital goods is less than the present value of the stream of returns they will earn in the future, investment will increase, and vice versa. The zero profit condition for investment $-\Pi_t^I \geq 0$ has the capital formation activity, I_t, as its associated dual variable. That is, there is no investment in equilibrium unless the unit cost of investment equals the price of capital stock in the next period.

Household behavior

The behavior of the consumer can be thought of as a sequence of decisions. Once the household has decided on the aggregate intertemporal full consumption for each period, it decides on to allocate consumption within each period. The allocation problem within each nesting level can, in turn, also be treated separately.

The household decides on aggregate full consumption for each period by maximizing the intertemporal utility function (22) under the restriction that the present value of consumption does not exceed the present value of income. That is,

$$\max U(C_t) \qquad \text{s.t.} \ \sum_{t=0}^{\infty} p_t^C C_t \leq INC. \tag{41}$$

The solution to this intertemporal problem yields intertemporal income balance and an optimal consumption sequence. The relation between full consumption in subsequent periods along the optimal path is

$$\frac{C_{t+1}}{C_t} = \left(\frac{p_{t+1}^C (1+\Delta)}{p_t^C} \right)^{-\sigma}, \tag{42}$$

where p_t^C are the full consumption (intraperiod utility) price indices. As noted earlier, these prices are in present value terms. The slope of the optimal consumption path will hence depend on the relation between the rate of time preference and the interest rate. If the interest rate is greater than Δ, full consumption will be rising over time due to an increase in savings, and vice versa.

At the next level, the intraperiod maximization yields the condition for the representative agent's full consumption

$$\Pi^C = p^C - \left(\gamma_{GS}(p^{GS})^{1-\sigma_{CL}} + \gamma_L (p^L)^{1-\sigma_{CL}}\right)^{1/(1-\sigma_{CL})}, \tag{43}$$

where the second term is the unit expenditure function. p^{GS} is the price index for commodities consumption

$$p^{GS} = \left(\gamma_{NEG}(p^{NEG})^{1-\sigma_{GS}} + \gamma_{EG}(p^{EG})^{1-\sigma_{GS}}\right)^{1/(1-\sigma_{GS})}, \tag{44}$$

and analogous for p^L and the composite good prices corresponding to the deeper CES nests, (20) to (22). The "zero profit" condition $-\Pi_t^C \geq 0$ has C_t, i.e. the household's full consumption, as the associated dual variable.

Government behavior

The government minimizes the cost of providing the exogenously given level of public goods and services, $\overline{GOVC_t}$, through the infinite horizon. In each time period *t*, cost minimization yields the "profit" of public good provision described by

$$\Pi^{GVT} = p^{GVT} - \sum_{i \in NE} a_{GVTi} p_i^A \left(1 + \tau_{GVTi}^A\right) - a_{GVTEG} p^{GVTE}, \tag{45}$$

where the energy composite price is

$$p^{GVTE} = \left(\sum_{i \in EN} \gamma_{GVTEi} \left(p_i^A (1 + \tau_{GVTi}^A)\right)^{1-\sigma_{GVTE}} \right)^{1/(1-\sigma_{GVTE})}. \tag{46}$$

$\overline{GOVC}$ is the dual variable to government "zero profit", $-\Pi^{GVT} \geq 0$.

The government balances its budget intertemporally, i.e. the budget constraint takes the following form

$$\sum_{t=0}^{\infty} p_t^{GVT} \overline{GOVT_t} = \sum_{t=0}^{\infty} TR_t - \theta^{LT} LT_t. \tag{47}$$

This constraint is accommodated through endogenous scaling of one of the government's tax instruments or through lump-sum taxation as described in the next subsection.

Market clearing

Market equilibrium requires that supply equals demand for all traded goods and factors. That is, in every period, the market clears for domestic output, export, import, and all primary factors. Note that each market clearing condition is associated with its dual non-negative price variable for the corresponding good or factor. Using Shepard's lemma, the market clearance condition for sectoral output Y_j is described by

$$Y_j = \sum_i Z_i \frac{\partial \Pi_i^Z}{\partial p_j}, \qquad \forall i \notin EP. \tag{48}$$

The domestic output of goods and the imported goods form the Armington composite goods that is used as intermediate inputs in production, capital formation, public good production or consumed by the private consumer, i.e. for domestic output destined for the domestic market the supply-demand balance is

$$Z_i \frac{\partial \Pi_i^Z}{\partial\left(p_i^D(1-\tau_i^{DX})\right)} = A_i \frac{\partial \Pi_i^A}{\partial p_i^D}, \qquad \forall i \notin EP, \tag{49}$$

and

$$Y_j^m \frac{\partial \Pi_j^m}{\partial\left(p_i^D(1-\tau_i^{DX})\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial\left(p_i^D(1-\tau_i^{DX})\right)} = A_i \frac{\partial \Pi_i^A}{\partial p_i^D}, \qquad \forall i \in EP. \tag{50}$$

Market clearance for each Armington good i is described by

$$\begin{aligned} A_i = \sum_j Y_j^m \frac{\partial \Pi_j^m}{\partial\left(p_i^A(1+\tau_{ji}^A)\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial\left(p_i^A(1+\tau_{ji}^A)\right)} + I \frac{\partial \Pi^I}{\partial\left(p_i^A(1+\tau_{Ii}^A)\right)} + \\ C \frac{\partial \Pi^C}{\partial\left(p_i^A(1+\tau_{Ci}^A)\right)} + GOVC \frac{\partial \Pi^{GVT}}{\partial\left(p_i^A(1+\tau_{GVTi}^A)\right)}. \end{aligned} \qquad \forall i. \tag{51}$$

Supply-demand balance for imports is

$$M_i = A_i \frac{\partial \Pi_i^A}{\partial\left(p_i^M(1+\tau_i^M)\right)}, \qquad \forall i, \tag{52}$$

and for exports

$$X_i = Z_i \frac{\partial \Pi_i^Z}{\partial \left(p_i^X (1-\tau_i^{DX})\right)}, \qquad \forall i \notin EP, \tag{53}$$

$$X_i = Y_j^m \frac{\partial \Pi_j^m}{\partial \left(p_i^X (1-\tau_i^{DX})\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial \left(p_i^X (1-\tau_i^{DX})\right)}, \qquad \forall i \in EP. \tag{54}$$

The world closure rule imposed requires trade balance. Here, the trade closure rule takes the form of an intertemporal balance of payment constraint that ensures no change in net indebtedness over the model horizon. The intertemporal trade balance is hence described by

$$\sum_{t=1}^{\infty} \sum_i \bar{p}_{it}^X X_{it} + BM_t = \sum_{t=1}^{\infty} \sum_i \bar{p}_{it}^M M_{it}, \tag{55}$$

where BM_t is the (present value) net capital inflow observed in the benchmark data, exogenously specified to remain at the benchmark level. Import and export prices are exogenously fixed in accordance with the assumption that Sweden is a small open economy, and therefore faces perfectly elastic export demand and import supply curves at the world market. The trade balance constraint (55) is associated with a "real exchange rate", that is adjusted so that the constraint is satisfied. Note that this intertemporal trade balance implies that borrowing and lending in terms of physical goods will be endogenously determined in the model. This means that the domestic real interest rate will equal the world market rate in steady state. The use of Armington goods in capital formation and the endogenous prices of domestically produced goods will, however, imply that the domestic interest can differ from the world rate during the transition from one steady state to another.

The market clearance condition for labor services in each period requires the exogenous labor endowment to be used in production or consumed by the household, i.e. the intra-period market clearance for skilled and unskilled labor respectively is

$$\overline{LS} = \sum_j Y_j^m \frac{\partial \Pi_j^m}{\partial \left(p^{LS} (1+\tau_j^{LS})\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial \left(p^{LS} (1+\tau_j^{LS})\right)} + C \frac{\partial \Pi^C}{\partial p^{LS}} \tag{56}$$

and

$$\overline{LU} = \sum_j Y_j^m \frac{\partial \Pi_j^m}{\partial \left(p^{LU} (1+\tau_j^{LU})\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial \left(p^{LU} (1+\tau_j^{LU})\right)} + C \frac{\partial \Pi^C}{\partial p^{LU}}. \tag{57}$$

The intra-period supply-demand balance for the malleable and non-malleable capital service is

$$K = \sum_j Y_j^m \frac{\partial \Pi_j^m}{\partial\left(p^K (1+\tau_j^K)\right)} \tag{58}$$

and

$$IK_j = Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial\left(p^{IK_j} (1+\tau_j^K)\right)} \qquad \forall j, \tag{59}$$

respectively. Finally, the supply equals the demand for each sector-specific natural resource service in each period

$$NR_j = Y_j^m \frac{\partial \Pi_j^m}{\partial\left(p^{NR_j} (1+\tau_j^K)\right)} + Y_j^{nm} \frac{\partial \Pi_j^{nm}}{\partial\left(p^{NR_j} (1+\tau_j^K)\right)} \tag{60}$$

2.7 Additional constraints

Equal yield tax constraints

The taxes τ^A, τ^K, τ^{LS} and τ^{LU} all consist of several taxes that, in turn, are associated with auxiliary constraints. The taxes are given by

$$\tau_{qi,t}^A = \sum_{h \in POLL} \theta_t^h tx_{qi}^h + tx_{qi}^A, \qquad \forall q,i \tag{61}$$

$$\tau_j^K = tx_j^{VA} + tx_j^K, \qquad \forall j \tag{62}$$

$$\tau_j^l = tx_j^{VA} + \theta_l^{PR} tx_{lj}^{PR} + \theta_l^{IT} tx_l^{IT}, \qquad \forall j,l \tag{63}$$

where the θ^{PR} and θ^{IT} are tax multipliers that endogenously scale the (exogenously) chosen replacement tax to accommodate the government budget constraint (47). Alternatively, lump sum taxation (transfers) can be used to fulfill the constraint through endogenous scaling of the multiplier θ^T in equations (25) and (47). Note that the budget constraint is satisfied by the means of a single parameter that proportionally scales the tax in *all* periods.

Emission constraints

The model endogenously calculates sector-specific emission levels for three pollutants, CO_2, NO_x and SO_2. The emission of these pollutants depends on each sector's use of polluting fossil fuels and their activity level. That is, the domestic emission level in each time period is described by

$$F^h = \sum_q \sum_{i \in PE} \mu_{qi}^h A_{qi} + \sum_j \eta_j^h Y_j \qquad h \in POLL, \tag{64}$$

where μ_{qi} is the consumer and sector-specific emission coefficient for input of fossil fuel good i. The parameter η_j is the sum of emissions from industrial processes, and also includes emissions originating from the use of "other fuels" that are not explicitly modeled, e.g. biofuels, per unit of output in sector j. All these emission parameters follow an exogenously determined time path.

The θ_t^h in (61) are endogenous tax multipliers for each of the three pollutants, each associated with an emission constraint

$$F_t^h \le \overline{F}_t^h, \qquad h \in POLL, \tag{65}$$

where $\overline{F}_t^h$ is the exogenously specified emission target level for pollutant h at time t. That is, if an emission target is specified, then the tax multiplier is adjusted until the inequality (65) is satisfied.

2.8 Calibration and terminal constraints

Steady state calibration

The basis for calibrating the model is the benchmark data set described in the next section together with assumptions about elasticities, the future steady state growth rate and capital depreciation rate. The benchmark social accounting matrix (SAM) is assumed to represent a point on the economy's steady state path. Given the steady state growth and capital depreciation rate, the SAM is projected into the future to generate the baseline data where all quantities grow at the exogenous Harrod-neutral growth rate, and all present value prices decay at the interest rate.

In the SAM, there is no direct information on the steady state interest rate. However, given the assumption that the economy is on its steady state growth path, it is possible to calculate the interest rate. From the observed investment level and the return to capital together with the assumed growth rate and capital depreciation rate, the unobserved benchmark capital stock can be calculated. In steady state, investment must cover capital growth less depreciation. From this relation, the benchmark capital stock is given by

$$K_0 = \frac{I_0}{(g+\delta)}, \tag{66}$$

where g is the steady state growth rate. The return to one unit of capital stock, p_0^K, is the observed benchmark capital supply divided by the benchmark capital stock, K_0. The interest rate, r, will equal this return less depreciation,

$$r = p_0^K - \delta. \tag{67}$$

The price per unit of benchmark capital is the given by

$$P_0^K = 1 + r. \tag{68}$$

Given these benchmark prices and quantities, together with the other values from the SAM, the equilibrium path quantities are the benchmark quantities times $(1+g)^t$ and the equilibrium path prices are the benchmark prices times $(1+r)^{-t}$.

Terminal constraint

Clearly, an infinite horizon CGE model can only be solved numerically for a finite number of periods. Therefore, a procedure is needed to approximate the infinite horizon. For relatively large models, a finite-horizon version of the model is solved with a horizon sufficiently long in order not to significantly affect the allocation. A very long horizon could, however, lead to an excessively large model dimension and, hence, computational problems. Given that the infinite horizon needs to be truncated in the model, imposing some terminal constraint on investment is necessary. The common procedure is to constrain terminal period investment to be large enough for the capital stock to grow at the steady state growth rate in the terminal period. This terminal constraint is, however, not utilized in this model. Instead, the procedure suggested in Lau et al. (2000) is adopted. They suggest a specification where the level of post-terminal capital is an endogenous variable and an inclusion of a constraint on the terminal period growth rate of investment. One of the advantages of this approach is that the model needs fewer periods to approximate the infinite horizon saddle path, relative the steady state growth constraint.[12] The terminal constraint used here requires the investment growth rate to equal the growth rate of consumption in the terminal period, i.e. if T denotes the terminal period the constraint is

$$\frac{I_T}{I_{T-1}} = \frac{C_T}{C_{T-1}}. \tag{69}$$

This constraint ensures that the investment grows at a balanced rate but does not require the model to achieve steady state in the terminal period.

Table 2.4 Variables and parameters

Variables and parameters	Description
Y_j	Total output in sector j
Y_j^m	Output in sector j by the production technology using malleable capital
Y_j^{nm}	Output in sector j by the production technology using sector-specific capital
A_i	Armington aggregate of domestic supply and imports of good i
A_{gi}, A_{Ii}	Use of Armington good i in intermediate, final and capital formation.
Z_i	Domestic output of good i
D_i	Domestic sales of good i
X_i	Export of good i
M_i	Import of good i
K	Capital stock
K_j	Malleable capital inputs to sector j
IK_j	Sector- specific capital inputs to sector j
NR_j	Natural resource inputs to sector j
LU_j	Unskilled labor inputs to sector j
LS_j	Skilled labor inputs to sector j
LU_{RA}	Private consumer demand for (unskilled) leisure
LS_{RA}	Private consumer demand for (skilled) leisure
I	Output from the capital formation activity
C	Private consumer full consumption
$GOVC$	Government consumption
U	Welfare index for the private consumer
INC	Private consumer income (present value)
BM	Current account balance (present value)
TR	Tax revenues (present value)
p_j	Price of domestic output from sector j (present value)
p_i^Z	Price of domestically produced good i (present value)
p_i^A	Net price of Armington good i (present value)
p_i^X	Export price of good i (present value)
p_i^D	Price of domestically produced good i for domestic market (present value)
$p^{LU}, p^{LS}, p^{NR_j}, p^K, p^{IK_j}$	Net labor, natural resource and capital rental prices (present value)

[12] See Lau et al. (2000) for a discussion and an evaluation of the relative precision of this approach.

Table 2.4 (cont.)

Variables and parameters	Description
P^K	Price of capital (present value)
τ_{qi}^A, τ_{Ii}^A	Composite ad valorem taxes on good i used for intermediate and final consumption and investment
$\tau_j^{LU}, \tau_j^{LS}, \tau_j^K$	Composite ad valorem taxes on primary factor use
τ_i^{DX}, τ_i^M	Ad valorem taxes on domestically produced and import tariff good i
tx_{ji}^h, tx_{ji}^A	Ad valorem user- specific emission and goods taxes on intermediate and final use of good i
$tx_j^{VA}, tx_j^K, tx_{lj}^{PR}, tx_l^{IT}$	Ad valorem value added, capital, payroll, and income taxes
LT	Lump sum transfers from the government to the private consumer
θ^h	Tax multipliers associated with constraints on emission h
$\theta^{PR}, \theta^{IT}, \theta^{LT}$	Tax multipliers on payroll tax, labor income tax and lump- sum transfers associated with government budget constraint
F^h	Aggregate emission of pollutant h
B, γ, α, a, b	Scaling and share parameters in production and consumption functions
σ	Elasticities of substitution
ε	Elasticities of transformation
Δ	Annual discount rate
r	Annual interest rate
g	Annual growth rate
δ_K	Annual capital depreciation rate
μ_{qi}^h	Emission coefficient for pollutant h and input i consumed by q
η_j^h	Process emission coefficient for pollutant h in sector j

3. Data and Parameter values

As is customary in computable general equilibrium analysis, the model is parameterized using information contained in economic data from the benchmark year, supplemented by emission data and other exogenous parameter values found in the literature. With the assumption that the (projected) balanced data represents an equilibrium, the parameters are chosen such that the model can reproduce this data set as a "benchmark" equilibrium solution.

Benchmark data

The benchmark economic data set used in the model represents Sweden in the year 1993. The basic social accounting matrix is based on input-output tables by Statistics Sweden (SCB) and The Swedish National Institute of Economic Research (NIER). The data on production and consumption of fossil fuel have been further disaggregated by using data published in SCB (1995). The emission data used in the model describes each sector's emission of CO_2, SO_2 and NO_x , divided into the use of different fossil fuels and emission from industrial combustion. These sector-specific emission coefficients are based on unpublished calculations by Statistics Sweden. Table 3.1 provides an overview of the benchmark economic activity and the pattern of *aggregate* emissions by the industry sectors and consumers included in the model.

Table 3.1 Some benchmark economic and emission data

					Emissions[d]	
Sector	Output[a]	Labor use[b]	Capital use[c]	CO_2	SO_2	NO_x
Agriculture	29.3	4.3	10.2	1377,0	0,6	19,0
Forestry	19.6	4.1	10.7	424,0	0,1	13,8
Fishing	1.0	0.1	0.5	157,0	0,1	4,7
Food and Textile[e]	177.7	34.3	21.1	4660,0	12,0	15,8
Pulp and Paper[e]	117.2	27.1	17.7	1972,0	17,6	16,0
Chemical[e]	75.8	15.5	14.4	2025,0	3,9	4,3
Steel and Metal[e]	49.7	8.9	3.4	6374,0	8,8	6,6
Manufacturing[e]	313.1	91.2	24.1	1005,0	0,7	2,6
Water and Sewage	10.4	0.8	5.9	20,0	0,0	1,0
Construction	157.3	61.9	16.9	1466,0	0,5	5,9
Transport	130.8	41.6	20.1	11892,0	22,1	119,6
Trade and Services	589.0	237.4	116.3	3416,0	0,6	55,7
Dwelling	276.0	18.0	196.9	717,0	1,1	2,1
Electricity and Heating	54.6	7.2	29.6	8876,4	15,1	16,0
Gas	1.7	0.1	0.6	16,6	0	0
Petroleum[e]	26.5	0.8	5.6	1739,0	5,8	3,9
Mining[e]	9.8	2.4	1.0	441,0	2,6	4,6
Private Consumer				14749,0	6,0	102,0
Government				1994,0	1,0	3,0

Source: SCB (1996)
a) Excluding taxes and subsidies. (Billion SEK_{93})
b) Including social security payments. (Billion SEK_{93})
c) Capital consumption and net operating surplus. (Billion SEK_{93})
d) SO_2, NO_x and CO_2 emissions in 1000 ton. CO_2 emissions excluding emissions from biofuels.
e) Sectors with lower environmental tax rates.

The model is calibrated to the 1993 tax system, which roughly has a similar environmental and energy tax structure (and exemptions) as the tax system today. The ad valorem fossil fuel tax rates used in the model are calculated by using yearly average fuel prices. Weighted average prices have been used in the cases where these prices differ between energy users. The benchmark energy prices used in the tax calculations are retrieved from SPI (1994) and NUTEK (1997). At the benchmark, the (exempted) industry is levied full SO_2 tax, one fourth of the CO_2 tax, and zero energy and electricity tax, on all energy inputs except gasoline and diesel for which they pay full tax. The sectors with these lower tax rates are indicated in Table 3.1. There is also a possibility for some sectors to receive a refund if certain pollution reducing actions are taken. At the benchmark, these actions result in some industrial sectors only paying approximately half the SO_2 tax rate. Electricity is taxed as an output, therefore electricity production pays zero energy and CO_2 tax. They do, however, pay full SO_2 tax on their inputs.[13] The electricity tax is only levied on non-industrial users. There is no NO_x tax at the benchmark, but there is a refundable NO_x charge only applying to heat and power plants. This charge is not explicitly included in the model.

Elasticities and other parameters

Elasticity values have to 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 these values, reliable econometric estimates are scarce, and the values used are therefore subject to a margin of error. To explore the effect of the elasticity values on results from fossil fuel related environmental policy, a sensitivity analysis where these values are perturbed is carried out in the next subsection.

The probably most important elasticity values for energy-related environmental policy assessments are the elasticities of substitution between energy-capital-labor inputs in production, and between different energy goods and other goods in consumption. The labor-capital-energy elasticity values used in the production functions are sector-specific estimates from Kemfert and Welsch (1997). These values are, on average, slightly higher than the "standard" elasticity values often used in energy-environmental related simulation models.[14] Simulations with the "standard" values are undertaken in the next section to assess the effect of changes in these elasticity values. Due to the lack of sector-specific estimates, the energy-energy elasticity values are uniform across sectors and assumed to be 0.6, which is in line with the "standard" values found in the literature. Private consumers' elasticity of substitution between energy and non-energy goods is set to 0.4. The energy-energy elasticities are assumed to be higher than and equal to the producing sectors' elasticity in private and public consumption, respectively.

The Armington trade elasticities used are, due to the lack of good econometric estimates, assumed to be 4.0 and equal for all sectors and consumers. Compared with values commonly used in simulation models, these values could be considered to be on the higher side, but are in line with values used by e.g. Harrison et al. (1997).[15] Labor supply elasticity is set to 0.5,

[13] The electricity sector also includes (a relatively small) production of district heating that is levied taxes on there fossil fuel use. These taxes are modeled as reduced tax rates for fossil fuel inputs into this sector.
[14] See Burniaux et al. (1992) for an overview.
[15] See Bhattarai et al. (1999) and Devarajan et al. (1997) for a discussion on the effects of the Armington elasticity value.

and the labor endowment assumed to be 1.25 times higher than the labor supplied in the benchmark data. The resulting aggregate labor supply elasticity is approximately 0.12.[16]

Other exogenous parameters used in the simulations are the sectorally uniform Harrod-neutral growth rate and the depreciation rate that equal 1.8 and 4 percent annually, respectively.[17] These values, together with the benchmark data set, yield a real interest rate close to 0.5 percent. Finally, the benchmark sector-specific (clay) capital share is set to 0.9 to create a short run capital adjustment cost.

Table 3.2 Some key parameters and elasticities used in the model

Description	Value
Steady state growth rate	0.018
Steady state depreciation rate	0.04
"Clay" share in putty-clay specification (All sectors)	0.90
Production[a]	
Elasticity of substitution between non-energy intermediate inputs and the composite of primary factors and energy inputs	0.0
Elasticity of substitution between labor aggregate and a composite of energy goods and capital.	0.58-0.94[b]
Elasticity of substitution between unskilled and skilled labor	1.2
Elasticity of substitution between capital and energy goods.	0.17-0.98[c]
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6
Elasticity of transformation between heavy fuel oil and other fuels in the petroleum sector	4.0
elasticity of transformation between coal and other mining outputs in the mining sector	4.0
Elasticity of transformation between goods for domestic market and goods for export market	4.0
Armington elasticity of substitution between imported and domestically produced goods	4.0[d]
Private Consumption	
Elasticity of substitution between aggregate leisure and a composite of all goods	0.5
Elasticity of substitution between skilled and unskilled leisure	0.5
Elasticity of substitution between aggregate non-energy goods and a composite of energy goods	0.4
Elasticity of substitution between different non-energy goods	1.01
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	1.01
Intertemporal elasticity of substitution	0.5
Government consumption	
Elasticity of substitution between different non-energy goods and a composite of energy goods	0.0
Elasticity of substitution between gas, coal, heavy fuel oil, other petroleum fuels and electricity	0.6

a) The input elasticity values apply to the "putty" part of the partial putty-clay production function. The corresponding values for the "clay" part are all equal to zero except for the Armington elasticities, which are equal to the same values as for the "putty" part.
b) 0.58 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.62 in paper and pulp. 0.76 in food and textile. 0.85 in chemical. 0.87 in transport. 0.92 in steel and metal. 0.94 in mining.
c) 0.17 in steel and metal. 0.31 in transport. 0.49 in chemical. 0.75 in food and textile. 0.87 in agriculture, forestry, fishing, petroleum, manufacturing, electricity, gas, water, construction, trade, dwelling. 0.91 in paper and pulp. 0.98 in mining.
d) Equal in production and consumption.

4. Sensitivity analysis of some illustrative policy experiments

To illustrate the sensitivity to the changes in capital adjustment cost, model structure and elasticity values, a simple environmental-energy related policy is simulated. The policy,

[16] Note that, the specification of leisure as a CES nest of "unskilled" and "skilled" leisure will result in a higher skilled or unskilled labor supply elasticity, relative the aggregate labor supply elasticity. That is, the possibility to substitute skilled leisure for unskilled leisure (and vice versa) increases the supply sensitivity to labor-type specific price changes.

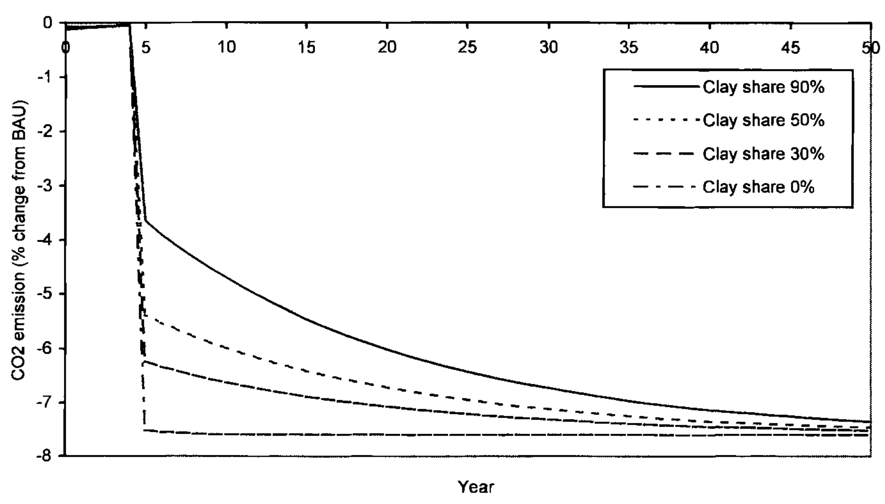
[17] 1.8 percent growth is slightly higher than the average Swedish growth rate during the period 1970-1990 but slightly lower than the growth rate in the 1990's. 4 percent capital depreciation rate is in line with the average value for the EEC used in simulations by e.g. Jacoby and Wing (1999).

which affects the price of fossil fuels, involves a permanent 100 percent increase of the benchmark (ad valorem) CO_2 tax. The tax change will take place in year 4 but is "announced" in the benchmark year. The policy results will be compared to the reference calibrated steady state path described above. To enable calculations of impact on welfare, the public good provision is maintained in the simulations. That is, the government's equal yield constraint is satisfied by endogenous changes in the payroll tax. The model is solved for 50 years in one-year time steps by using the PATH solver (Ferris and Dirkse, 1995).

The effects of the partial putty-clay specification

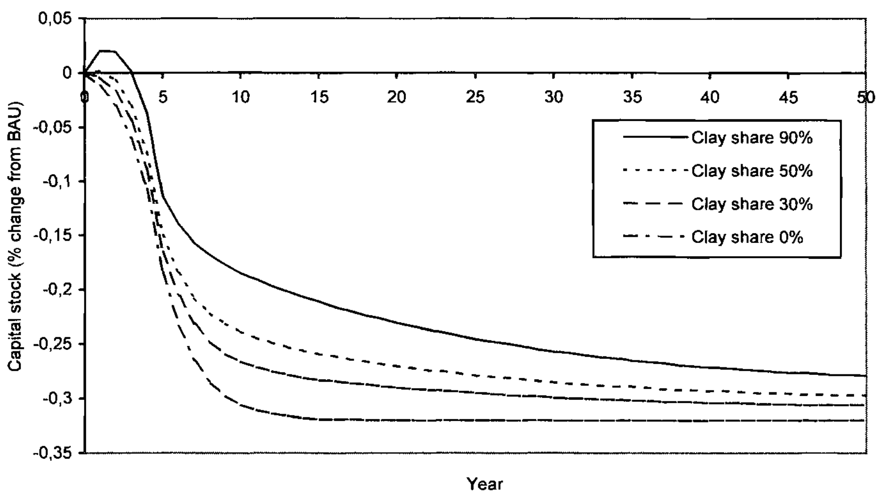
The process of capital adjustment under policy pressure cannot be regarded as well understood. The specification chosen can significantly influence the adjustment cost and hence, the outcome of energy/environmental related policies. The partial putty-clay specification reproduces the empirically observed energy price elasticity, which tends to be inelastic in the short run and elastic in the long run. The specification yields a low elasticity of energy use in the short run, due to the fixed proportions of energy and non-malleable capital. In the long run, when a larger share of capital input is malleable, the specification results in a more responsive energy use with respect to differences in energy prices. Furthermore, in a policy scenario, premature retirement of extant capital will occur if the (part of) production technology using sector-specific capital becomes unprofitable.

Figure 4.1 CO2 emission paths with different putty-clay assumptions



The CO_2 tax policy experiment yields the CO_2 abatement curves shown in figure 4.1 corresponding to different assumptions about the benchmark clay share of capital in all sectors. The effects of the aggregate capital stock, i.e. malleable and sector-specific capital, are shown in figure 4.2. It is clear that an assumption of perfectly malleable capital results in an immediate adjustment to the long-run abatement level of almost 8 percent. This does not fit very well with the empirical observation of low price elasticities for energy use in the short run. A larger share of clay capital yields a result closer to observed behavior. The emission abatement increases when the tax is introduced[18], and continues to increase toward the long run level at a decreasing rate as the energy-energy and energy-capital-labor substitutability increases with extant capital depreciation and new investment. Note that the CO_2 tax mainly works as a tax on fossil fuel use and hence, should not be directly compared with an increase in energy price. The tax will, for example, result in an increased use of domestic and imported electricity.

Figure 4.2 Total capital stock paths with different putty-clay assumptions



The effects of an alternative form of nesting structure

The nesting structure used in the production function is clearly not the only possible choice available, and other plausible structures exist. The most important nesting for energy-environmental policy related work is probably the nesting between capital, energy and labor. Besides the structure presented in the above model description, a nesting structure where

[18] Note that the tax increase also applies to the consumers that have better short run substitution possibilities.

capital and labor are substituted for each other in a lower nest and then, as an aggregate, substituted for energy, is also commonly used in applied models. The former nesting structure is proposed by Burniaux et al. (1991), and applied in their GREEN model, and the latter is the structure proposed by Manne and Richels (1992), and applied in their Global 2100 model.

To assess the assumption of capital-energy-labor substitutability, the CO_2 tax scenario is simulated with two different nesting assumptions. The two basic nesting structures are assessed. First, the structure presented above, i.e. capital-energy aggregate substituted against labor aggregate is used with both the sector-specific elasticities estimated by Kemfert and Welsch (1997), and the "standard" elasticities suggested by Burniaux et al. (1991). Second, the model is reformulated to a nesting structure where a capital-labor nest is substituted for an energy nest with "standard" elasticities used by Manne and Richels (1992). The partial putty-clay assumption implies that, in all nesting structures, the main part of the production will have small substitution possibilities in the short run when the share of extant capital is large. In the long run, however, the different types of nesting structures will have larger impact on the outcome.

The results, presented in Table 4.1, indicate that the effect on final year GDP does not differ substantially between all three models. The reduced payroll taxes from recycled CO_2 tax revenue result in a small increase in labor input, and are also roughly comparable in between models. Larger differences between the models are observed in the capital-CO_2 intensity. With highly complementary energy and capital with the "Burniaux elasticities", higher energy prices result in a (long run) relatively more CO_2 intensive capital stock.

Table 4.1 A Comparison between different nesting structures and elasticities.

	Labor, (Capital, Energy)		(Capital, Labor), Energy
	Kemfert-Welsch	Burniaux et al.	Manne-Richels
Elasticities:			
Capital-Energy:Labor	0.58-0.94[a]	0.6	
Capital:Energy	0.17-0.98[a]	0.3	
Capital-Labor:Energy			0.4
Capital:Labor			1.0
Welfare effect (%EV)	-0.301	-0.267	-0.268
Long run effects:[b]			
GDP	-0.503	-0.529	-0.514
Labor aggregate	0.026	0.029	0.028
Capital aggregate	-0.265	-0.430	-0.369
CO_2 emissions	-7.955	-5.895	-6.223
CO_2/Capital	-7.710	-5.489	-5.876

[a] Sector-specific estimates as shown in Table 3.2.
[b] All effects in percent change relative BAU in end period (Year 50).

The, on average, higher substitution elasticities estimated by Kemfert-Welch result in greater substitution toward capital input and, hence, a more CO_2 efficient capital stock. Finally, in Manne-Richels specification, the substitution from fossil fuels results in a somewhat more CO_2 efficient capital stock. The welfare effects, measured in percent equivalent variation relatively to the BAU present value income (%EV), indicate that with a relatively more rigid production technology, the CO_2 tax is less costly. In terms of welfare cost per quantity of reduced CO_2 emissions, however, a more rigid structure is more costly.

The effects of changes in elasticity of substitution values

Clearly, the simulations with the different nesting structures and elasticity values above do not give a complete "feeling" for the robustness of the results for different combinations of elasticity values. To further assess this, a sensitivity analysis based on the procedures developed by Harrison and Vinod (1992)[19] is carried out next. The procedures are basically a Monte Carlo simulation exercise, in which a wide range of elasticities are independently and simultaneously perturbed from their base values. In lack of standard errors for the elasticity values used, each input elasticity (including the Armington elasticity) is given a relatively wide uniform distribution around its base value.[20] The model is then repeatedly solved for the CO_2 policy scenario used above. For each Monte Carlo run, a new set of elasticities is randomly drawn from the given distributions. This procedure is repeated until a sample size of 1020 is reached. The resulting mean, median, maximum, minimum, and standard deviation for some key endogenous variables are presented in Table 4.2.

Table 4.2 Key variable results from sensitivity analysis (Sample size 1020)

	With point estimate values[a]	Mean	Median	Maximum	Minimum	Standard deviation
Welfare (%EV)	-0.301	-0.314	-0.311	-0.185	-0.465	0.0538
GDP[b]	-0.503	-0.517	-0.513	-0.361	-0.707	0.0581
CO_2 emissions[b]	-7.955	-8.135	-8.115	-5.677	-10.293	0.8236

[a] Elasticity values shown in Table 3.2

[b] Percent change relative BAU in end period (Year 50).

The simulations indicate that the results from the policy reform are relatively robust to uncertainty over input elasticities. That is, the mean value of the welfare cost (-%EV), the effect on final period GDP and final period CO_2 emission reduction resulting from the perturbed elasticity simulations are of the same order as the results obtained by the point

[19] See also Harrison et al. (1993)

[20] Clearly, the elasticity value distributions has to be truncated at zero, which produces skewed distributions, especially for the production nest characterized by a Leontief technology.

estimates elasticity values. Furthermore, the means are close to the medians, and the standard deviations are not uncomfortably high.

5. Concluding remarks

This paper has presented a dynamic, multi-sectoral, small-open-economy CGE model for the Swedish economy. The model has been developed mainly for environmental policy assessments, and is therefore aggregated to a dimension for which reliable environmental data are available.

Needless to say, the present version of the model has limitations, and several improvements are possible. Among the most important improvements for environmental related policy analysis is to develop the not completely satisfactory treatment of energy supply. Although this is a limitation in most top-down models, the modeling format allows for a relatively straightforward extension to include "bottom-up" energy activities as suggested by Böhringer (1998). Another important limitation, which clearly is more difficult to resolve, is the treatment of technological development. The inclusion of endogenous technological development in energy production is a potential extension that might be considered in future model developments.

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