Climate and Competitiveness: An Economic Impact Assessment of EU Leadership in Emission Control Policies

Victoria Alexeeva-Talebi, Christoph Böhringer and Ulf Moslener

Centre for European Economic Research (ZEW)

P.O. Box 103443, 68034 Mannheim, Germany. Email: alexeeva-talebi@zew.de

Abstract. The European Council has recently claimed to consider ambitious emission reduction targets (15 to 30 percent by 2020 as compared to 1990 levels) to limit global climate change. In the light of the coexistent EU priorities under the Lisbon process, we analyse alternative unilateral EU emission control policies against their effects on EU (sectoral and economy-wide) competitiveness using a multi-sector, multi-region computable general equilibrium (CGE) model framework. For a given emission reduction target, our simulations show that alternative implementation rules (uniform versus sectorally differentiated carbon taxes) induce ambiguous impacts on sectoral competitiveness: For a uniform tax, relatively carbon-intensive EU industries face competitiveness losses, while carbon-extensive sectors improve their ability to compete internationally. Losses and gains are reinforced by the stringency of unilateral emission reduction targets. Thus, the implementation of an (economically efficient) uniform carbon tax induces structural change which inevitably goes at the expense of carbon-intensive industries. Vice versa, we find that more pronounced tax differentiation in favor of carbon-intensive industries can largely neutralize the negative impacts of emission constraints on their competitiveness, but goes at the expense of overall efficiency. In this case, adjustment costs of emission abatement will to a large extent be borne by energy-extensive sectors in terms of a deteriorated ability to compete. As a middle course, moderate tax differentiation allows to sectorally balance competitiveness effects of emission control policies and at the same time limit overall efficiency losses. We find also that the level of tax differentiation to balance sectoral competitiveness effects and to limit overall efficiency losses is independent of the emission reduction target. Furthermore, our results indicate that the magnitude of sectoral competitiveness effects is sensitive to the selection of competitiveness indicators.

JEL Classification: D58, H21, H22, Q48

Keywords: Competitiveness Indicators, Computable General Equilibrium (CGE) Models, Kyoto Protocol

1 Introduction

International concern about climate change has led to the signature of the Kyoto Protocol in 1997, constituting emission reduction targets of averagely five percent for industrialized countries during the commitment period 2008-2012. Initially, the Protocol was celebrated as a breakthrough in international climate policy. However, the U.S. withdrawal from the Protocol and a potential supply of excess emission permits suggests that the first commitment period of the Kyoto Protocol is likely to accomplish very little in terms of global emission reduction (Böhringer, 2002). In order to limit an average global temperature increase to a maximum of 2°C, the European Council has recently claimed to consider ambitious emission reduction targets of 15 to 30 percent by 2020 as compared to 1990 levels (European Commission, 2007).

In 2000, the European Council has also launched the so-called Lisbon process establishing the issue of competitiveness as a priority area for EU policy. Since then the term "competitiveness" has turned into a catchword in virtually every political debate on new regulatory proposals. Envisaging the Lisbon strategy, the stringency of environmental policy should be therefore assessed with respect to the effects on competitiveness.

The majority of previous quantitative studies on EU emission control policies does not explicitly account for international competitiveness effects. Therefore, Oberndorfer and Rennings (2006) recently suggested using a "cost-based approach" to assess competitiveness effects of the EU ETS. Furthermore, several simulation studies apply a "macro-indicator based approach" to assess the competitiveness effects of climate policies in the EU by means of standard macroeconomic indicators such as output and welfare (Rinaud, 2005; Klepper and Peterson 2004). In our view, compliance costs of emission regulations *determine* competitiveness effects, while recursively changes in macroeconomic indicators may result from changes in competitiveness but do not measure these effects. Only very few simulation studies explicitly account for the competitiveness effects in terms of productivity (profitability) (Carbon Trust, 2004; COWI, 2004) and to our knowledge only one simulation study assesses international competitiveness effects of the EU ETS for energy-intensive industries by means of the Revealed Comparative Advantage (RCA) indicator (Klepper and Peterson, 2004).

Against this background, the contribution of this paper is threefold: Firstly, we review and systematize alternative competitiveness concepts in order to present a generalized definition for competitiveness at firm, sectoral and economy-wide level and specify appropriate indicators. Based on this approach, we are able to assess the performance of selected competitiveness and macro-indicators. Secondly, we analyse sectoral (including energy-intensive and energy-extensive sectors) and economy-wide competitiveness effects for alternative unilateral EU emission control policies, i.e. alternative emission reduction targets, assuming a uniform (tax) treatment across sectors. The degree of EU leadership in emission control policies is measured by emission reduction targets ranging from 5 to 30 percent reductions versus the base year emission level. Thirdly, we quantify trade-offs between efficiency and (sectoral and economy-wide) competitiveness effects for a given emission reduction target assuming alternative levels of sectoral tax differentiation.

Our results demonstrate that alternative implementation rules (uniform versus sectorally differentiated carbon taxes) for a given emission reduction target induce ambiguous impacts on competitiveness: For a uniform tax, relatively carbon-intensive EU industries face competitiveness losses, while carbon-extensive sectors improve their ability to compete internationally. Losses and gains are reinforced by the stringency of unilateral emission reduction targets. Thus, the implementation of an (economically efficient) uniform carbon tax induces structural change which inevitably goes at the expense of carbon-intensive industries. Vice versa, more pronounced tax differentiation in favor of carbon-intensive industries can largely neutralize the negative impacts of emission constraints on their competitiveness, but goes at the expense of overall efficiency. In this case, adjustment costs of emission abatement will to a large extent be borne by energy-extensive sectors in terms of a deteriorated ability to compete. As a middle course, moderate tax differentiation allows to sectorally balance competitiveness effects of emission control policies and at the same time limit overall efficiency losses. We find also that level of tax differentiation to balance sectoral competitiveness effects and to limit overall efficiency losses is independent of the emission reduction target. Furthermore, our results indicate that the magnitude of sectoral competitiveness effects is sensitive to the selection of competitiveness indicators.

The remainder of this paper is structured as follows: Section 2 reviews competitiveness concepts at the firm, sector and national level and discusses sectoral competitiveness indicators that are subsequently implemented in a computable general equilibrium model framework. Section 3 provides a model-based policy assessment of competitiveness effects of unilateral EU carbon emission restrictions. Section 4 concludes. A detailed algebraic description of the static core model version is given in the appendix.

2 Competitiveness Indicators

2.1 Notations of Competitiveness

The concept of competitiveness has proven to be hard to define and susceptible for ambiguities. The main reason for this is that the scope of competitiveness concept is rather comprehensive and thus complex to make it operational for a quantitative policy analysis. In order to come up with a pragmatic approach on assessing competitiveness implications of policy interference, the scientific community has developed a huge variety of competitiveness indicators, while national governments and international organizations started implementing them on a regularly basis to assess for competitiveness implications. The selection of the competitiveness indicators appears however often to be poorly justified or even arbitrary (Reichel, 2002). For example, European Commission (EU, 2005) evaluates sectoral competitiveness performance of EU industries using a range of competitiveness indicators but does not indicate precise selection criteria for these indicators. Moreover, clear distinction between indicators which operationalize the competitiveness (*competitiveness indicators*) and indicators which determine the competitiveness (*competitiveness determinants*) is often missing.[1]

To address these shortcomings, we first review competitiveness notations at firm, sectoral and national level.[2] One of the difficulties in analyzing these issues arises from the fact the competitiveness concept is relatively well defined at the firm level[3] but remains rather vague and controversial at the sectoral and national level. Thus, we present a generalized version of competitiveness definition at each level synthesizing alternative competitiveness notations. We then specify competitiveness indicators that may be used to measure the competitiveness and link them explicitly to the generalized competitiveness notations. We cover the competitiveness determinants only marginally since their selection should be based on the sound economic theory to account for a clear cause and effect chain.

2.1.1 Competitiveness at the firm level

Competitiveness at the firm level concerns the performance of individual firms relative to their competitors in a particular market. Reviewing the literature on alternative competitiveness concepts allows us to conclude that the performance of individual firms relative to their competitors resides in (i) "ability to sell" (Sell, 2003; Martin, 2004) and (ii) "ability to earn" (President's Commission on Industrial Competitiveness, 1985; Liebe, 1982; Sell, 2003; Martin, 2004). In this respect, the "ability to sell" corresponds to the firm's success at the market, while the "ability to earn" is associated with the firm's profit performance. Referring to (i), market share may be used as an example of competitiveness indicators to measure the firm's success at the market, i.e. "ability to sell". Referring to (ii), profit may be selected as a competitiveness indicator to measure the firm's "ability to earn". Then, the qualitative and quantitative competitiveness determinants like productivity, unit costs, product quality, delivery times, R&D expenditures, after-sales services, financing arrangements, technological innovations, investments in physical and human capital, etc. determine the recent and future competitiveness at the firm level, i.e. the "ability to sell" and "ability to earn", rather than measure it (Berg, 1981; Priewe, 1996; Hitchens et al., 1998; Havlik et al. 2001).

2.1.2 Competitiveness at the sectoral level

Competitiveness at the sectoral level is an important policy issue since many countries feature a limited number of sectors appearing most relevant for domestic economic performance. Consequently, national and international stake-holders release the assessments of policy issues on the sectoral competitiveness on a regularly basis (see e.g. EU 2004). Search for an

[1] Reichel (2002) interprets the former indicators as "success indicators" and the latter as "success determinants".
[2] This differentiation is generally attributed to the different nature of the competition between the economic entities at the appropriate level (Sell, 1991; Tuchtfeldt, 1992; Klepper and Peterson, 2003).
[3] OECD (1996).

appropriate definition of competitiveness at the sectoral level has proven to be rather challenging. While few contributors reject competitiveness concept at the sectoral level (Reiljan and Kulu, 2002), some others provide a very general definition (Priewe, 1996) or give an implicit definition[4] rather than an explicit one (Trabold, 1995, Kriegsmann and Neu, 1982; Havlik et al., 2001; EU, 2004). Summarizing explicit and implicit contributions on this issue, we argue that the competitiveness at the sectoral level resides in (i) "ability to sell" (Priewe 1996, EU 2004; Havlik et al., 2001) and (ii) "ability to earn" (Sell, 2003; Hevlik et al., 2001). Referring to the "ability to sell", a range of competitiveness indicators have yet been proposed. While the absolute measures (e.g. export ratios, import ratios) are appealing and commonly used in the contributions on the competitiveness at the sectoral level (EU, 2005), the relative measures such as Revealed Comparative Advantages (RCA), Relative World Trade Share (RWS) or the Relative Trade Balance (RTB) should be preferred from a theoretical point of view[5]. Referring to the "ability to earn", profitability of industry may be used as an appropriate competitiveness indicator at the sectoral level. Competitiveness determinants at the sectoral level are similar to those at the firm level, e.g. productivity (labour, capital, total, multifactor productivity)[6], R&D expenditures, innovation potential or investment flow. In addition, following Porter (1999), the analysis of clustering as competitiveness determinants may be also taken into consideration.

2.1.3 Competitiveness at the national level

Concept of competitiveness at the national level has been discussed rather controversially for many decades. Fundamental criticism on this concept comes however from one of the most prominent members of the scientific community Paul Krugman (1991, 1994, 1999, 2004). In order to avoid an unnecessary overlapping, we refer to Reichel (2002) who addressed Krugman's skepticism in a comprehensive way and conclude that concept of competitiveness at the national level appears to be meaningful. Summarizing the literature, we conclude that nation's competitiveness at the national level resides in: i) "ability to earn" (e.g. Auerbach, 1996, Berthold, 1994; Dollar and Wolff, 1993; EU, 2000; EU 2004; OECD, 1992; Reichel 2002; RWI, 1983; Sell, 1991; 2003; Trabold, 1995), ii) "ability to sell" (Balassa, 1962; PCIC, 1984/85; Dollar and Wolff; 1993; Trabold, 1995), iii) "ability to attract" (Flassbeck, 1992; PCIC, 1984/85; Staubhaar, 1997; Trabold 1995) and iv) "ability to adjust" (PCIC, 1984/85; Sell, 1991; Trabold, 1995). Referring to (i), "ability to earn" corresponds to the achievements of an economy as to income. Referring to (ii), "ability to sell" refers to the performance of an economy at the international markets. Referring to (iii), "ability to attract" implies the economy's achievements in attracting the production factors. Referring to (iv), "ability to adjust" implies the capability of an economy to adapt to new conditions.

Table 1 provides a selection of competitiveness indicators at the national level according to four classifications ("abilities") presented above. Obviously, it may be difficult to distinguish

[4] Several contributions use competitiveness indicators to describe competitiveness.
[5] We refer to these indicators in more detail in the section 3.3.1.
[6] See e.g. OECD (2001).

to which ability a certain indicator belongs to. For some areas, especially within the "ability to adjust", it can be hard to find meaningful indicators at all.

Table 1: List of competitiveness indicators at the national level

Ability to sell	**Ability to earn**	**Ability to attract**	**Ability to adjust**
• Current account • Terms of trade • Real exchange rate • World market share • Revealed comparative advantage	• (Per capita) income • [Technological competitiveness] • (Labor-) productivity • [Human capital]	• Net foreign direct investment • Corporate tax burden • Level of wages • [Infrastructure] • [Labor market regulation] • Unemployment rate	• [Adjustment to new supply / demand structure] • [Flexibility of wages] • [Flexibility of exchange rates]

N.B.: Entries in brackets show areas where a number of indicators can be defined but are not further specified here.

With respect to competitiveness determinants, we will not specify them and refer to theoretical and empirical literature since the discussion of these indicators would go beyond the scope of this section.

2.2 What indicators for what models?

There is a wide range of quantitative models which may assess the causal chains between a proposed policy change and its potential competitiveness implications. Models mainly differ with respect to the emphasis placed on (i) sectoral details versus economy-wide scope (bottom-up sector-level models vs. top-down macroeconomic models), (ii) econometric foundation of functional relationships (econometrically estimated models vs. calibrated models when parameters of functional forms are simply selected to fit a single empirical observation, and (iii) the richness of behavioral assumptions for economic agents (micro-founded models vs. macro-founded models).

As to numerical model-based analysis of competitiveness effects, the question which of the indicators at the level of firms, sectors, or countries can be implemented depends on the specific modeling framework. The common dichotomy between top-down economy-wide models and bottom-up sectoral models appears to be important. Yet, the aggregation level of these models is not sufficient to address the competitiveness effects at the firm level due to level of aggregation. Moreover, while the standard bottom-up approach is restricted to the quantification of the competitiveness at the sectoral level, a general equilibrium modeling framework is able to assess competitiveness effects at sectoral and economy-wide level. Despite a relatively high aggregation level, a general equilibrium modeling framework possesses several advantages for quantifying competitiveness effects: Firstly, assessing (relative) sectoral and national-wide "ability to sell" is inherently a general-equilibrium phenomenon that can be studied only in a setting of general equilibrium (Haaland et al., 1988). Secondly, a general equilibrium approach allows for quantification of possible trade-offs in competitiveness effects at the sectoral and national level. This is important since the quantification of possible trade-offs between competitiveness effects at the different levels is a prerequisite for any rational debate on competitiveness.

In what follows, we discuss in more detail three indicators - "Relative World Trade Shares" (RWS), "Relative Trade Balance" (RTB) and "Revealed Comparative Advantage" (RCA) - which are used to describe international competitiveness in terms of "ability to sell" and will be directly amenable to CGE-based policy analysis in section 3. RTB index and RWA index stem from the European Commission (EU 2005) and are complemented by the RCA index which is very common but surprisingly does not appear in this report. Thus, in our analysis of competitiveness effects we restrict our focus to competitiveness indicators measuring the "ability to sell" and will not consider the relevant competitiveness determinants.

2.3 Selected Sectoral Indicators for CGE-Analysis

The concept of Revealed Comparative Advantage (RCA) may be referred to as the empirical counterpart to the theoretical concept of comparative advantage. The extensive literature offers a variety of definitions for RCA which may be mapped to three groups reflecting the different data input choice (observable variables): i) RCA indicators based on production and trade statistics; ii) RCA indicators based on trade statistics only and iii) RCA indicators based on deviations between actual and expected values of production and consumption.

In this section, we consider a version index of the Revealed Comparative Advantage (the RCA index) initially proposed by Balassa (1965) which belongs to the group of the trade-based indicators. This concept is concerned with the competitiveness of different industries within an economy. For a particular region and sector, this index compares the ratio of exports by a specific sector over its imports with the ratio of exports over imports across all sectors of the region. Letting *X* denote exports, *M* imports, *i* the region and *j* the sector, the index for revealed comparative advantage (RCA) for region *i* in sector *j* can be presented as follows[7]:

$$RCA_{ij} = \frac{X_{ij} / M_{ij}}{\sum_j X_{ij} / \sum_j M_{ij}}$$

If the sectoral export-import ratio is identical to the economy-wide ratio, the RCA index takes the neutral value of one ($RCA_{ij} = 1$). Thus, a region *i* is said to have a revealed comparative advantage in sector *j* if the RCA index exceeds unity ($1 < RCA \leq \infty$). By contrast, a region *i* has a revealed comparative disadvantage in sector *j* if the RCA index takes the values between zero and one ($0 \leq RCA < 1$). Thus, the lack of symmetry between the value ranges for comparative advantage ($1 < RCA \leq \infty$) and comparative disadvantage ($0 \leq RCA < 1$) is one of the major shortages in this index definition. Up to now, this version of the RCA index has been used by Halbherr et al. (1998), DIW (1995a) and Thießen (1995). There is a range of

[7] There is a range of slightly different RCA measures and normalization approaches (for mapping the index to the range between zero and one). Here we use the normalized version of the Balassa-index proposed by Münt (1996).

slightly different RCA measures and normalization approaches for mapping the index to the range between zero and one.[8]

A similar attempt to quantify sector-specific competitiveness is the one that uses relative world trade shares (RWS)[9]. This index compares the ratio of country's exports in a certain sector over the world's exports in this sector with the ratio of country's overall exports over the world's exports in all sectors:

$$RWS_{ij} = \frac{X_{ij} / \sum_i X_{ij}}{\sum_j X_{ij} / \sum_i \sum_j X_{ij}} .$$

RWS indicator posses the same value range as RCA indicator ($0 \leq RWS_{ij} \leq \infty$) and thus may be interpreted in a similar way. The normalized version of RWS indicator is also available.[10]

Finally, we refer to Relative Trade Balance (RTB) index which compares the trade balance (exports minus imports) for a product to the total trade (exports plus imports) of that product.

$$RTB_{ij} = \frac{X_{ij} - M_{ij}}{X_{ij} + M_{ij}}$$

This index posses the neutral value of zero ($RTB_{ij} = 0$) and the value range of $-1 \leq RTB_{ij} \leq 1$. Slightly different measures of RTB indicators have been proposed by Balance (1988), Sell (1991) and Preuße (1991).[11]

Table 3 summarizes the main properties of the sectoral indicators discussed above and makes it clear that the comparability of these indicators is to some extent restricted. This refers particularly to the divergent value ranges of RCA/RWS and RTB on the one hand and to the lack of symmetry by RCA/RWS on the other hand. Moreover, while RCA and RWA indicate whether the competitiveness of a particular sector lies above (below) average in the country, the RTB does not allow for the comparison between the sectors within one region.

---

[8] Münt (1996) has proposed the following normalized version of Balassa indicator with the neutral value of zero and the value range of range $-100 \leq RCA \leq 100$:

$$RCA^a_{ij} = 100 \cdot \tanh \cdot \ln\left(\frac{X_{ij} / M_{ij}}{\sum_j X_{ij} / \sum_j M_{ij}}\right)$$

[9] This indicator is occasionally referred as RCA indicator (EU 2005).

[10] Gehrke and Grupp (1994), Maurer (1994) and Münt (1996). Münt (1996) presents the normalized version of the indicator with the range $-100 \leq RWA \leq 100$:

$$RWA_{ij} = 100 \cdot \tanh \cdot \ln\left(\frac{X_{ij} / \sum_i X_{ij}}{\sum_j X_{ij} / \sum_j M_{ij}}\right)$$

[11] The slightly different version of the relative net export ratio is proposed by Sell (1991):

$$RCA_{ij} = \left[\frac{X_{ij} - M_{ij}}{X_{ij} + M_{ij}} - \frac{\sum (X_{ik} - M_{ik})}{\sum (X_{ik} + M_{ik})}\right] * 100 \text{ for } k \neq j$$

The neutral value of this indicator is zero and the value range is $-200 \leq RCA \leq 200$. However, it is also possible to normalize this indicator for the range $-100 \leq RCA \leq 100$ (Gahlen, 1986; Sell, 1991).

Table 3: Main Properties of the selected sectoral indicators

Indicator	Neutral Value	Symmetry	Value Range
RCA	1	No	$0 \leq RCA \leq \infty$
RWA	1	No	$0 \leq RWA \leq \infty$
RTB	0	Yes	$-1 \leq RTB \leq 1$

To make the results comparable and interpretable, Reichel (2002) requires the indicators to possess the following features: i) symmetry in the value range, ii) the neutral value of zero and iii) the bound value range. This argument would support the usage of the normalized versions of the indicators. However, the properties of the indicator may be altered through the implied normalization procedure. Thus, in our analysis we stick to the non-normalized versions of the competitiveness indicators RCA, RWS and RTB.

Finally, in order to clarify our understanding of what is exactly being measured by RCA, RWS and RTB, we may think the “ability to sell” as consisting of four success components: i) “ability to sell by home producers (sectors) at domestic markets”, ii) “ability to sell by home producers (sectors) at foreign markets, ii) “ability to sell by foreign producers (sectors) at domestic markets” and (iv) “ability to sell by foreign producers (sectors) at foreign markets”. All these abilities may be measured by means of absolute and relative indicators. The relative indicators are however constructed in such a way that they compare at least two different abilities and differ with respect to the reference point: RTB and RCA include the abilities (i) and (iii) but differ with respect to the reference point. RWS includes the ability (i), (ii) and (iii). Thus, these measures are in a sense meaningful as they imply different relative concepts, i.e. comparing different dimensions of “ability to sell” and using different reference points.

3 Policy Application: EU Leadership in Climate Policy

3.1 Policy Background

The apparent “failure” of the Kyoto Protocol with respect to environmental effectiveness does not come much as a surprise from the perspective of standard economic theory given the lack of a supranational authority and the huge free-riding incentives in global public good provision. The rationale behind free-riding in climate policy is to save abatement costs while benefiting from abatement efforts of other countries. Although all countries could be better off if they behaved in a cooperative way, each country has an incentive to take a free-ride. This may lead to the well-known “tragedy of the commons”. Despite of this prisoners' dilemma situation there might be reasons for single countries to take a leading role and act unilaterally. For example, a country may decide to make short-term sacrifices in the expectation of long run benefits from an increase in the number of signatory countries. Another motivation which is especially relevant in the EU context could be the domestic political environment where voters demand concrete environmental action. As a matter of fact, the EU is viewing itself as the key promoter of climate protection activities. At the same time, EU policy makers fear negative impacts on international competitiveness of key energy-intensive industries when adopting (much) stricter emission regulation as compared to trading partners.

Apart from adverse implications of unilateral emission regulation on EU industries, there is a potentially important environmental dimension to sub-global action regarding climate change: Unilateral abatement may lead to an increase in emissions in non-abating regions, reducing the global environmental effectiveness. This phenomenon is referred to as "leakage". Emission leakage in the case of EU unilateral carbon abatement can be measured as the increase in non-EU emissions relative to the reduction in EU Member States. There are three basic channels through which carbon leakage can occur (Felder and Rutherford, 1993). First, leakage can arise when in countries undertaking emission limitations energy-intensive industries lose in competitiveness and the production of emission-intensive goods relocates raising emission levels in the non-participating regions (trade channel). Secondly, cut-backs of energy demands in a large region due to emission constraints may depress the demand for fossil fuels and thus induce a drop in world energy prices, which in turn could lead to an increase in the level of demand (and its composition) in other regions (energy channel). Thirdly, carbon leakage may be induced by changes in regional income (and thus energy demand) due to terms of trade changes. Leakage rates reflect the impact of sub-global emission abatement strategies on comparative advantage.

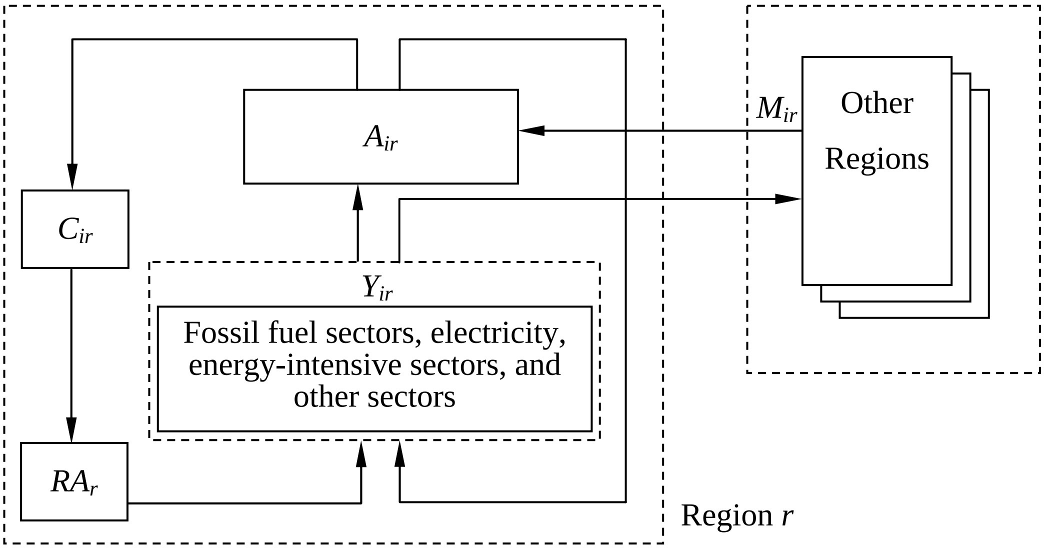
To reduce leakage and improve cost-efficiency of unilateral action, exemptions or tax-breaks for energy- and export-intensive industries are a commonly adopted strategy. However, an appropriate tax differentiation scheme would call for a careful accounting of embodied emissions in imports and exports. Otherwise, the cost of meeting a specific reduction target may increase substantially because the marginal cost of emission reduction are no longer equalized across sectors. At the practical level, the risk of potentially costly tax breaks to energy- and export-intensive sectors is apparent as managers of these politically influential industries use the leakage argument to push forward wide-ranging exemptions.

3.2 Non-technical Summary of the CGE Framework (PACE)

To investigate the implications of EU leadership in climate policy on sectoral competitiveness, gross economic welfare (abstracting from benefits of changes in environmental quality), and global carbon emissions, we make use of the static multi-sector, multi-region model PACE for the world economy.

Figure 1 lays out the diagrammatic structure of the core model. Primary factors of a region *r* include labor, capital, and resources of fossil fuels *ff* (crude oil, coal, and gas). The specific resource used in the production of crude oil, coal and gas results in upward sloping supply schedules. Production Y_{ir} of commodity *i* in region *r*, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs.

Figure 1: Diagrammatic overview of the model structure



Nested constant elasticity of substitution (CES) cost functions with several levels are employed to specify the substitution possibilities in domestic production sectors between capital, labor, energy, and non-energy intermediate inputs.

Final demand C_{ir} of the representative agent RA_r in each region is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. The substitution patterns within the non-energy consumption bundle as well as the energy aggregate are described by nested CES functions. CO_2 emissions are associated with fossil fuel consumption in production, investment, and final demand.

All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions, the so-called Armington good. Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. Endowments of primary resources are fixed exogenously. In the core simulations, we assume competitive factor and commodity markets such that prices adjust to clear these markets. Within our static framework, macroeconomic investment is fixed at the benchmark level (alternatively, we might introduce a marginal propensity to save or a model specification where the marginal costs of investment equals the return to investment given myopic expectations).

The model is based on most recent consistent accounts of production, consumption, bilateral trade and energy flows for 87 countries and 57 sectors provided by the GTAP 6 data base for the base year 2001 (Dimaranan and McDougall (2006)).

Table 4: Model dimensions

Production sectors	Regions and primary factors
Energy	*Regions*
Coal	European Union (EUR)
Crude oil	Non-EU OECD (OEC)
Natural gas	Rest of World (ROW)
Refined oil products (OIL)	
Electricity	
Non-Energy	*Primary factors*
Energy-intensive sectors (EIS)	Labor
Rest of industry and services (OTH)	Capital
Savings good	Fixed factor resources for coal, oil and gas

For the sake of compactness, we have aggregated the GTAP countries to 3 major regions: European Union (EUR), Non-EU OECD (OEC), and Rest of World (ROW). The sectoral aggregation in the model has been chosen to distinguish carbon-intensive sectors from the rest of the economy. It captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across carbon-intensive goods. The primary and secondary energy goods identified in the model are coal, natural gas, crude oil, refined oil products, and electricity. Important carbon-intensive and energy-intensive non-energy industries that are potentially most affected by carbon abatement policies are aggregated within a composite energy-intensive sector. The remaining manufacturers and services are aggregated to a composite industry that produces a non-energy-intensive macro good. The primary factors in the model include labor, physical capital, and fossil-fuel resources. Table 4 summarizes the regional, sectoral, and factor aggregation of the model.

3.3 Scenarios and Results

In order to illustrate the consequences of the European Union moving forward in terms of global climate policy we assume unilateral emission abatement within the EU while trading partners abstain from any comparable carbon emission regulation. We differentiate the unilateral EU policy along two central dimensions: Firstly, the degree of leadership measured in terms of the unilateral reduction target of EU emissions vis-à-vis the benchmark situation where no effective emission abatement policy applies; the emission reduction target is set subsequently at 5 %, 10 %, 15 %, 20 %, 25 %, and 30 % of the base year emission level. Secondly, the level of tax differentiation between carbon-intensive (non-electric) industries – EIS and OIL – and the rest of the economy; the ratio of implicit tax rates to achieve the exogenous EU emission reduction target ranges from unity (i.e. uniform carbon taxes), via factors of 2, 5, 10, and 20 to full exemption of the carbon-intensive industries. Ratios higher than one indicate that taxes are discriminated in favor of carbon-intensive industries – for example a ratio of 20 implies that the carbon tax rate in the rest of the economy is twenty times higher than for carbon-intensive industries.

We use contour plots over the unilateral emission abatement target and the tax ratio to visualize our results. Note that in the graphs we refer to the case of full tax exemptions of carbon intensive industries with a label "inf" for the associated *infinite* tax ratio.

3.3.1 Economic and environmental implications of EU carbon emission constraints

Figures 2 and 3 report the implications of unilateral EU carbon policies for economic welfare, implied carbon taxes, and carbon leakage. Neglecting environmental benefits from carbon abatement, unilateral emission constraints impose non-negligible welfare losses for the EU economy which increase towards higher reduction targets and more pronounced tax differentiation in favor of carbon-intensive industries. In our core simulations, welfare losses – measured as reduction in real consumption (here: Hicksian equivalent variation) – may amount to as much as 2.5 % for the case of fully exempting carbon-intensive industries and emission targets of 30 % (Figure 2a).

Figures 3a.-c. summarize the impacts of unilateral EU carbon policies on sectoral production of different industries. Imposition of carbon constraints induces structural change which inevitably goes at the expense of carbon-intensive industries. Towards higher emission reduction targets, the output losses for these industries may become drastic – in particular for the mineral oil industry. In turn, tax cuts may offset the adverse output effects for carbon-intensive industries to a large extent. While tax breaks are clearly beneficial for carbon-intensive industries, they go at the expense of the remaining industries (OTH) which are subject to relatively higher carbon tax rates to meet the exogenous overall emission reduction target. Output losses for these industries may substantially increase towards strong preferential tax treatment of carbon-intensive industries.

For the case of full exemption, the associated carbon values for the rest of the economy are displayed in Figure 2b which also yields – by means of the tax ratio – the lower carbon value for carbon-intensive industries. In this case, the carbon value imposed on the rest of the economy ranges up to several hundreds of $US per ton of carbon which explains the excess cost of discriminating policy regulations due to foregone cheap abatement options in the carbon-intensive segments of the economy.

Figure 2c. illustrates finally the problems of unilateral action in climate policy regarding global environmental effectiveness. For our model parameterization, a substantial part of EU abatement – around 30 % – is offset through increased emissions of non-regulating trading partners. Leakage rates are relatively robust with respect to the level of the emission reduction target. As expected, leakage rates decline with tax discrimination of carbon- and export-intensive industries – however, the magnitude of leakage reduction turns out to be rather small.

3.3.2 Competitiveness implications of EU carbon emission constraints

Figure 4a. reports the competitiveness effects at the national level being measured by the changes in the terms of trade, i.e. the index of the price of EU's exports in terms of its imports. The terms of trade deteriorate as that index falls. This indicator signals that the implications of more stringent unilateral emission reduction targets for competitiveness are unambiguously negative. More pronounced tax differentiation in favor of carbon-intensive industries may however improve the terms of trade due to the possibility of tax burden shifting via higher export prices of carbon-intensive products.

To evaluate the effects of the EU leadership on the sectoral competitiveness indicators, we first present the values for the indicators for BaU in Table 5. RCA, RWS and RTB indicate that the sectors OIL and GAS have a comparative disadvantage in business-as-usual equilibrium (RCA<1, RWS<1), while the ELE and EIS have a comparative advantage (RCA>1, RWS>1). The results with respect to the sector OTH are not uniform.

Table 5: EU Sectoral Competitiveness Indicators (BaU)

Sector	RCA	RWS	RTB
Oil	0,75	0,67	-0,13
Gas	0,35	0,39	-0,48
Ele	1,01	1,56	0,02
Eis	1,06	1,16	0,04
Oth	0,99	0,96	0,01

The competitiveness effects of the EU leadership in climate policy at the sectoral level are visualized in Figures 4b.-h. in terms of changes of RCA, RWS and RTB for EIS and OTH sectors. With uniform (tax) treatment, sectors which are relatively carbon-intensive lose competitiveness, whereas relatively carbon-extensive sectors gain in competitiveness according to all three competitiveness indicators (RCA, RTB, RWS). These indicators differ however in the magnitude of the losses (gains) in competitiveness. For example, while according to RCA and RWS sectoral competitiveness losses may amount to as much as 10% for EIS industries (by emission reduction targets of 30%), RTB reports a loss of competitiveness of more than 100%. Simultaneously, the improvement of competitiveness by OTH industries may amount more than 50% according to the RTB (by emission reduction targets of 30%) and uniform tax treatment, whereas RCA and RWS indicate a more moderate improvement in competitiveness of around 3%. Moreover, our results (based on RCA) imply that EIS sectors may loose their comparative advantage (in BaU) only for very high emission reduction targets and uniform tax treatment (starting from 25%), whereas OTH will receive a comparative advantage for relatively moderate targets (starting from 5%). Losses and gains are reinforced with the magnitude of unilateral emission reduction targets. However, tax differentiation in favor of carbon-intensive industries can largely "neutralize" the implications of emission constraints on sectoral competitiveness.

Our results highlight the critical significance of competitiveness indicators at the sectoral level. For a balanced view, it is important to account for changes across the various sectors of the domestic economy rather than focusing on a very narrow segment of the economy which might be most affected by policy-induced structural change. In addition, sectoral implications must be traded off with economy-wide impacts. Obviously, improvements in competitiveness for some industries may not only work at the expense of competitiveness of other industries but induce an overall loss in national competitiveness measured in terms of real income.

We have performed a sensitivity analysis for our results varying the values for the Armington elasticity, i.e. substitution elasticity between the import aggregates and the domestic production. Our results indicate that relative low values for the Armington elasticity imply a more difficult substitution between domestic and foreign production, thus reducing the negative competitiveness effects on the energy-intensive industries but also reducing the positive competitiveness effects on non-energy-intensive industries.

3.3.3 Cost implications of unilateral carbon restrictions for the EU

Figures 5a.-c. provide further insights into the economy-wide cost implications of unilateral abatement policies. Figure 5a. indicates the additional costs the EU would have to undergo in order to compensate for carbon leakage. The cost increase amounts to roughly 50 % to 100 % of a strategy without leakage compensation depending on the level of the unilateral emission target and the chosen tax differentiation. Figures 5b. and 5c. illustrate the cost implications of tax differentiation (i) for the realistic case when leakage is not compensated and (ii) for the rather unrealistic case of leakage compensation. If we do not account for leakage, larger tax differentiation may be costly in particular for higher unilateral reduction targets (although at lower reduction targets there might be some limited scope for exploiting terms of trade effects through tax discrimination vis-à-vis uniform taxation). If leakage must be compensated for, some degree of tax discrimination in favor of carbon-intensive industries may in fact be beneficial as compared to uniform taxation.

4 Conclusions

The European Council has recently claimed to consider ambitious emission reduction targets of 15 to 30 percent by 2020 as compared to 1990 level. Envisaging the Lisbon strategy, this paper analyses EU sectoral and economy-wide competitiveness effects for alternative unilateral EU emission control policies (i.e. alternative emission reduction targets) assuming uniform and sectorally differentiated carbon tax implementation. As a prerequisite for our study, we discuss alternative definitions of the term "competitiveness" and implement selected indicators at the sectoral and economy-wide level within a multi-sector, multi-region CGE model framework.

For a given emission reduction target, our simulations show that alternative implementation rules (uniform versus sectorally differentiated carbon taxes) induce ambiguous impacts on competitiveness: For a uniform tax, relatively carbon-intensive EU industries face competitiveness losses, while carbon-extensive sectors improve their ability to compete internationally. Losses and gains are reinforced by the stringency of unilateral emission reduction targets. Thus, the implementation of an (economically efficient) uniform carbon tax induces structural change which inevitably goes at the expense of carbon-intensive industries. Vice versa, more pronounced tax differentiation in favor of carbon-intensive industries can largely neutralize the negative impacts of emission constraints on their competitiveness, but goes at the expense of overall efficiency. In this case, adjustment costs of emission abatement will to a large extent be borne by energy-extensive sectors in terms of a deteriorated ability to compete. As a middle course, moderate tax differentiation allows to sectorally balance competitiveness effects of emission control policies and at the same time limit overall efficiency losses. The factor of tax differentiation to balance competitiveness effects and to limit overall efficiency losses is thereby independent of emission reduction targets. Furthermore, our results indicate that the magnitude of sectoral competitiveness effects is sensitive to the selection of competitiveness indicators.

Thus, when assessing competitiveness impacts of policy regulation at the sectoral level, it is important to trade off changes across all the sectors of the domestic economy rather than focusing on only a few branches which might be most exposed at first glance to policy measures. In addition, sectoral implications must be weighted against economy-wide impacts. As a matter of fact, improvements in competitiveness for some industries may not only work at the expense of competitiveness of other industries but induce an overall loss in national competitiveness and overall efficiency. Finally, our analysis warrants the careful and complementary use of alternative competitiveness indicators.

References

Auerbach, P. (1996), Firms, Competitiveness and the Global Economy, in: Mackintosh, M. et al., *Economics and Changing Economies*, London et al., 393-425.

Balassa, B. (1965), Trade liberalization and revealed comparative advantage, *The Manchester School of Economic and Social Studies* 33, 99-123.

Berthold, N. (1992a), Wettbewerbsfähigkeit der deutschen Wirtschaft – Gefahr in Verzug, Berlin.

Berthold, N. (1992b), Wettbewerbsfähigkeit der deutschen Wirtschaft – Ein Standortproblem?, in: Hamburger Jahrbuch für Wirtschafts- und Gesellschaftspolitik, 159-171.

Böhringer, C. (2002), Climate Politics From Kyoto to Bonn: From Little to Nothing?, *The Energy Journal* 23 (2), 51-71.

Dimaranan, B.V. and R.A. McDougall (2006), Global Trade, Assistance, and Production: The GTAP 6 Data Base, Center for Global Trade Analysis, Purdue University.

Felder, S. and T.F. Rutherford (1993), Unilateral Action and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials, *Journal of Environmental Economics and Management*, 25, 162-176.

EU (2003), Seventh edition of the Commission's Report on European competitiveness, European Commission, Brussels, download at:
http://europa.eu.int/comm/enterprise/enterprise_policy/competitiveness/doc/comprep_2003_e

EU (2004), Eight edition of the Commission's Report on European competitiveness, European Commission, Brussels, download at:
http://europa.eu.int/comm/enterprise/enterprise_policy/competitiveness/doc/comprep_2004_en.pdf

Hitchens, D., E. Birnie, A. McGowan, U. Triebswetter and A. Cottica (1998), *The Firm, Competitiveness and Environmental Regulations – A Study of the European Food Processing Industries*, Edward Elgar, Cheltenham.

Klepper, G. and S. Peterson (2003): "International Trade and Competitiveness Effects". *CATEP Emissions Trading Policy Briefs* 6. Environmental Institute, Dublin.

Krugman, P. R. (1991), Myths and Realities of U.S. Competitiveness, *Science* 254(8), 811 – 815.

Krugman, P. R. (1994), Competitiveness: A Dangerous Obsession, *Foreign Affairs* 73(2), 1 - 17

Krugman, P. R. (1999), *Der Mythos vom globalen Wirtschaftskrieg – Eine Abrechnung mit den Pop-Ökonomen*, Campus Verlag, Frankfurt/Main

Krugman, P. R. and M. Obstfeld, (2004), *Internationale Wirtschaft*, Pearson Studium, München

Martin, R. L. (2004), A Study on the Factors of Regional Competitiveness - A draft final report for The European Commission Directorate-General Regional Policy, Cambridge Econometrics.

OECD (2001), *Measuring Productivity – OECD Manual*, Paris.

Reichel, R. (2002), *Ökonomische Theorie der internationalen Wettbewerbsfähigkeit von Volkswirtschaften*, Deutscher Universitätsverlag, Wiesbaden.

Sell, A. (1991): *Einführung in die internationale Wirtschaftsbeziehungen*. Berlin, New York.

Sell, A. (2003): *Einführung in die internationale Wirtschaftsbeziehungen*. Oldenburg, München.

Shoven, J. B. and J. Whalley, (1984), Applied General-Equilibrium Models of Taxation and International Trade: An Intrudction and Survey, *Journal of Economic Literature* 22(3), 1007-1051.

Srinivasan, T. N. and J. Whalley (1986), General Equilibrium Trade Policy Modeling, MIT Press.

Trabold, H. (1995), Die internationale Wettbewerbsfähigkeit einer Volkswirtschaft, in: DIW (1995): *Vierteljahreshefte zur Wirtschaftsforschung*, Duncker&Humblot, Berlin, 169-185.

Tuchfeldt, A.G. and S.S. Golub (1992): Zum Problem der internationalen Wettbewerbsfähigkeit, in: Görgens, E./Tuchfeldt, E., *Die Zukunft der wirtschaftlichen Entwicklung: Perspektive und Probleme*, Bern et al., 363-384.

Appendix A

A1 Algebraic Model Summary

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_{ir}^{z} is used to denote the profit function of sector *j* in region *r* where *z* is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions.

We use *i* (aliased with *j*) as an index for commodities (sectors) and *r* (aliased with *s*) as an index for regions. The label *EG* represents the set of energy goods and the label *FF* denotes the subset of fossil fuels. Tables A.1 – A.6 explain the notations for variables and parameters employed within our algebraic exposition. Figures A.1 – A.4 provide a graphical exposition of the production and final consumption structure. Numerically, the model is formulated as a mixed complementarity problem (MCP) in GAMS.

Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{KLE} \left[\theta_{ir}^{E} p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E}) \left(w_r^{\alpha_{jr}^{L}} v_r^{\alpha_{jr}^{K}} \right)^{1-\sigma_{KLE}} \right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad i \notin FF$$

2. Production of fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q}) \left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_{j} \theta_{jir}^{FF} p_{jr}^{A} \right)^{1-\sigma_{Q,i}} \right]^{\frac{1}{1-\sigma_{Q,i}}} = 0 \qquad i \in FF$$

3. Sector-specific energy aggregate:

$$\prod_{ir}^{E} = p_{ir}^{E} - \left\{ \theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1-\theta_{ir}^{ELE}) \left[\theta_{ir}^{COA} p_{\{COA,r\}}^{A^{1-\sigma_{COA}}} + (1-\theta_{ir}^{COA}) \left(\prod_{j \in LQ} p_{jr}^{A^{\beta_{jir}}} \right)^{1-\sigma_{COA}} \right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}} = 0$$

4. Armington aggregate:

$$\prod_{ir}^{A} = p_{ir}^{A} - \left[\left(\theta_{ir}^{A} p_{ir}^{1-\sigma_A} + (1-\theta_{ir}^{A}) p_{ir}^{M^{1-\sigma_A}} \right)^{\frac{1}{1-\sigma_A}} + t_r^{CO2} a_i^{CO2} \right] = 0$$

5. Aggregate imports across import regions:

$$\prod_{ir}^{M} = p_{ir}^{M} - \left(\sum_{s} \theta_{isr}^{M} \; p_{is}^{X\;1-\sigma_M} \right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

$$\prod_{r}^{C} = p_{r}^{C} - \left(\theta_{Cr}^{E} \; p_{Cr}^{E\;1-\sigma_{EC}} + (1-\theta_{Cr}^{E}) \left[\prod_{i \notin FF} p_{ir}^{A^{\gamma_{ir}}} \;) \right]^{1-\sigma_{EC}} \right)^{\frac{1}{1-\sigma_{EC}}} = 0$$

7. Household energy demand:

$$\prod_{Cr}^{E} = p_{Cr}^{E} - \left[\sum_{i \in FF} \theta_{iCr}^{E} \; p_{ir}^{A\;1-\sigma_{FF,C}} \right]^{\frac{1}{1-\sigma_{FF,C}}} = 0$$

Market Clearance Conditions

8. Labor:

$$\overline{L}_r = \sum_{i} Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial w_r}$$

9. Capital:

$$\overline{K}_r = \sum_{i} Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial v_r}$$

10. Natural resources:

$$\overline{Q}_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial q_{ir}} \qquad i \in FF$$

11. Output for domestic markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}} = \sum_{j} A_{jr} \frac{\partial \Pi_{jr}^{A}}{\partial p_{ir}}$$

12. Output for export markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{X}} = \sum_{s} M_{is} \frac{\partial \Pi_{is}^{M}}{\partial p_{ir}^{X}}$$

13. Sector specific energy aggregate:

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

14. Import aggregate:

$$M_{ir} = A_{ir} \frac{\partial \Pi_{ir}^{A}}{\partial p_{ir}^{M}}$$

15. Armington aggregate:

$$A_{ir} = \sum_{j} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{A}} + C_r \frac{\partial \Pi_{r}^{C}}{\partial p_{ir}^{A}}$$

16. Household consumption:

$$C_r \, p_r^{C} = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + t_r^{CO2} \overline{CO2}_r + p_{CGD,r} \overline{Y}_{CGD,r} + \overline{B}_r$$

17. Aggregate household energy consumption:

$$E_{Cr} = C_r \frac{\partial \Pi_r^C}{\partial p_{Cr}^E}$$

18. Carbon emissions:

$$\overline{CO2}_r = \sum_i A_{ir} a_i^{CO2}$$

Table A.1: Sets

I	Sectors and goods
J	Aliased with i
R	Regions
S	Aliased with r
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

Table A.2: Activity variables

Y_{ir}	Production in sector *I* and region *r*
E_{ir}	Aggregate energy input in sector *i* and region *r*
M_{ir}	Aggregate imports of good *i* and region *r*
A_{dir}	Armington aggregate for demand category *d* of good *i* in region *r*
C_r	Aggregate household consumption in region *r*
E_{Cr}	Aggregate household energy consumption in region *r*

Table A.3: Price variables

p_{ir}	Output price of good *i* produced in region *r* for domestic market
p_{ir}^X	Output price of good *i* produced in region *r* for export market
p_{ir}^E	Price of aggregate energy in sector *i* and region *r*
p_{ir}^M	Import price aggregate for good *i* imported to region *r*
p_{ir}^A	Price of Armington good *i* in region *r*
p_r^C	Price of aggregate household consumption in region *r*
p_{Cr}^E	Price of aggregate household energy consumption in region *r*
w_r	Wage rate in region *r*

v_r	Price of capital services in region *r*
q_{ir}	Rent to natural resources in region *r* (i $\in$ FF)
t_r^{CO2}	CO_2 tax in region *r*

Table A.4: Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labor endowment for region r
$\overline{K}_r$	Aggregate capital endowment for region r
$\overline{Q}_{ir}$	Endowment of natural resource i for region r (i$\in$FF)
$\overline{B}_r$	Balance of payment deficit or surplus in region r (note: $\sum_r \overline{B}_r = 0$)
$\overline{CO_2}_r$	Endowment of carbon emission rights in region r
$a_i^{CO_2}$	Carbon emissions coefficient for fossil fuel i (i$\in$FF)

Table A.5: Cost shares

θ_{ir}^X	Share of exports in sector *i* and region *r*
θ_{jir}	Share of intermediate good *j* in sector *i* and region *r* (i$\notin$FF)
θ_{ir}^{KLE}	Share of KLE aggregate in sector *i* and region *r* (i$\notin$FF)
θ_{ir}^E	Share of energy in the KLE aggregate of sector *i* and region *r* (i$\notin$FF)
α_{ir}^T	Share of labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* (i$\notin$FF)
θ_{ir}^Q	Share of natural resources in sector *i* of region *r* (i$\in$FF)
θ_{Tir}^{FF}	Share of good *i* (*T*=*i*) or labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* (i$\in$FF)
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector *i* in region *r* (i$\notin$FF)
θ_{ir}^{ELE}	Share of electricity in energy demand by sector *i* in region *r*
β_{jir}	Share of liquid fossil fuel *j* in energy demand by sector *i* in region *r* (i$\notin$FF, j$\in$LQ)
θ_{isr}^M	Share of imports of good *i* from region *s* to region *r*
θ_{ir}^A	Share of domestic variety in Armington good *i* of region *r*
θ_{Cr}^E	Share of fossil fuel composite in aggregate household consumption in region *r*
γ_{ir}	Share of non-energy good *i* in non-energy household consumption demand in region *r*
θ_{iCr}^E	Share of fossil fuel *i* in household energy consumption in region *r*

Table A.6: Elasticities

η	Transformation between production for the domestic market and production for the export	2
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.8
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}	μ_{COA}=0.5 μ_{CRU}=1.0 μ_{GAS} =1.0
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.3
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_{A}	Substitution between the import aggregate and the domestic input	4
σ_{M}	Substitution between imports from different regions	8
σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

Figure A.1: Nesting in non-fossil fuel production

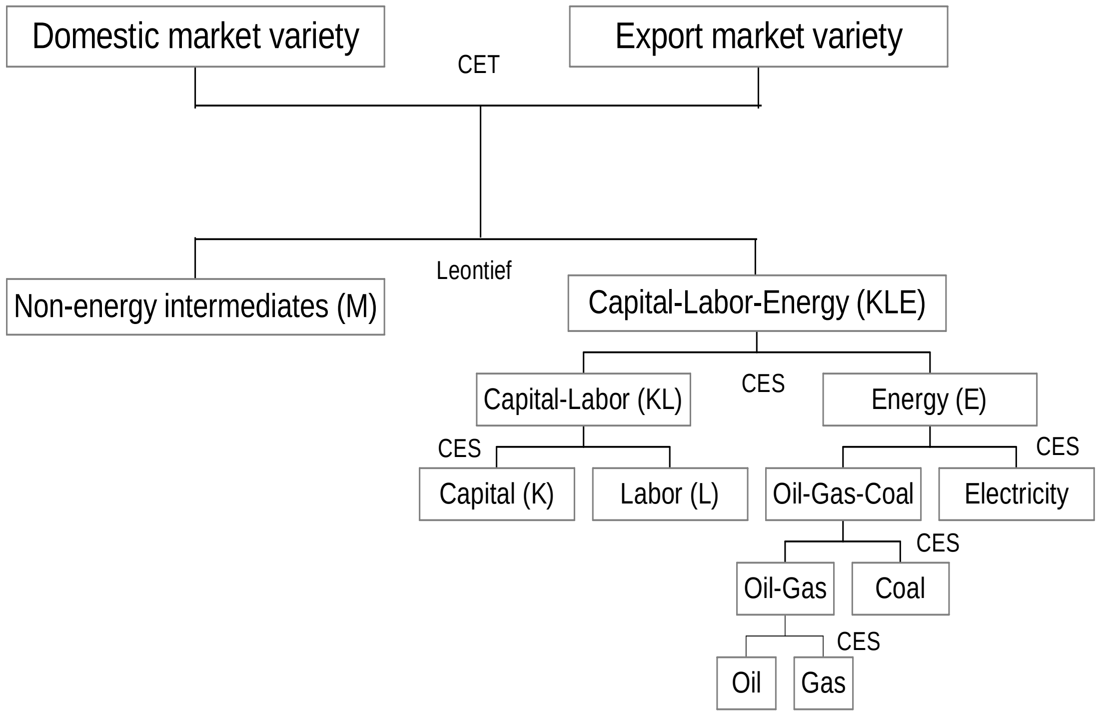


Figure A.2: Nesting in fossil fuel production

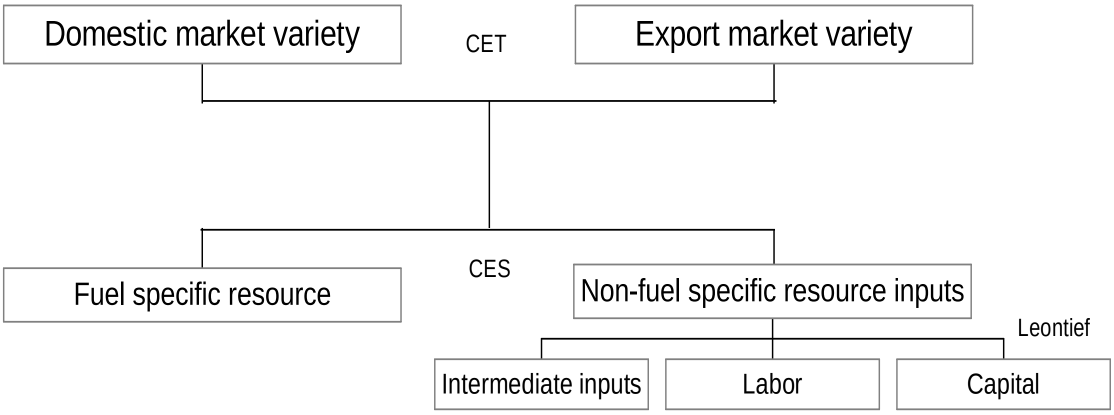


Figure A.3: Nesting in household consumption

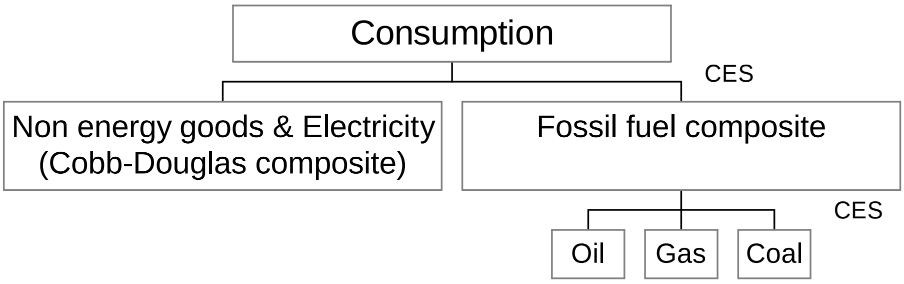
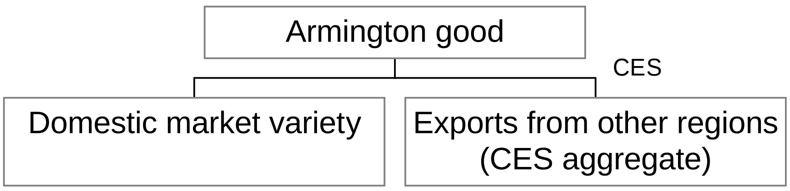


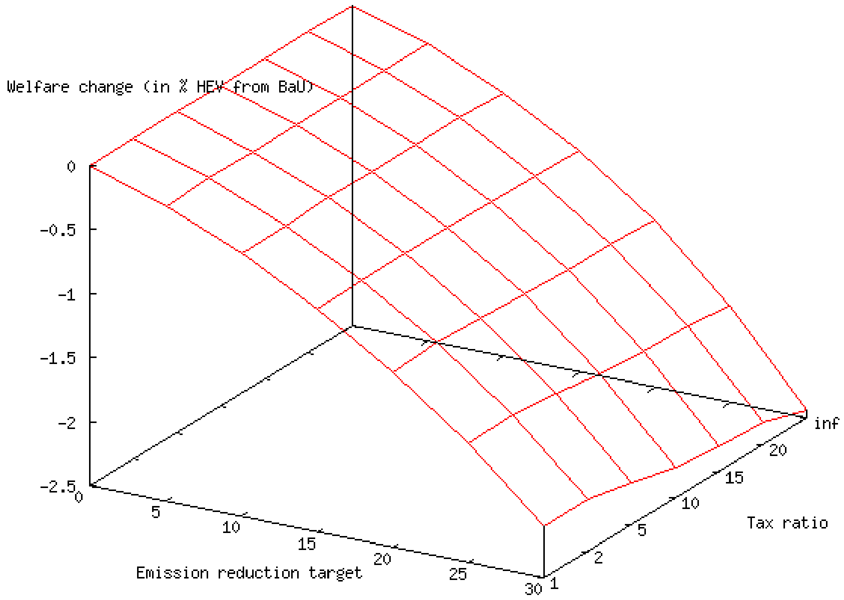
Figure A.4: Nesting in Armington production



A2 Figures

Figure 2: Economic and environmental implications of EU carbon emission constraints

a. Welfare (% HEV from BaU)



b. Carbon tax for rest of economy ($/t of C)

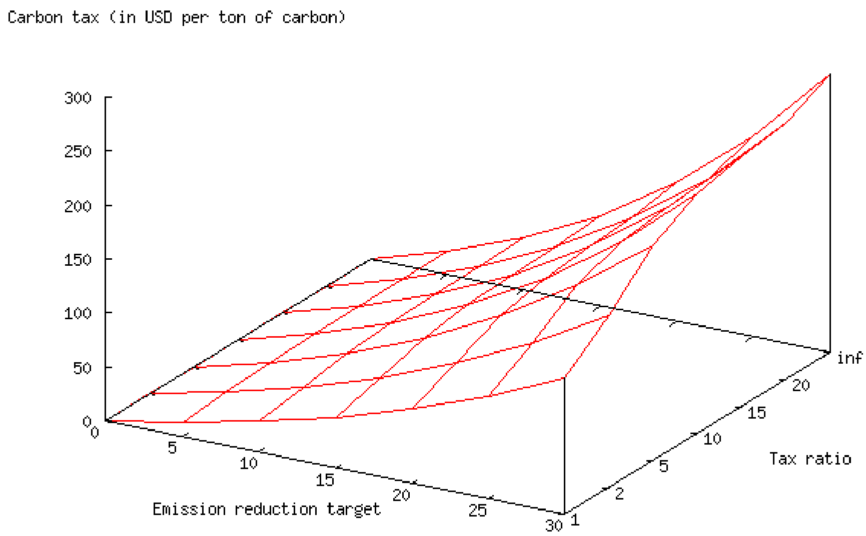


Figure 2: Economic and environmental implications of EU carbon emission constraints

d. Leakage (in %)

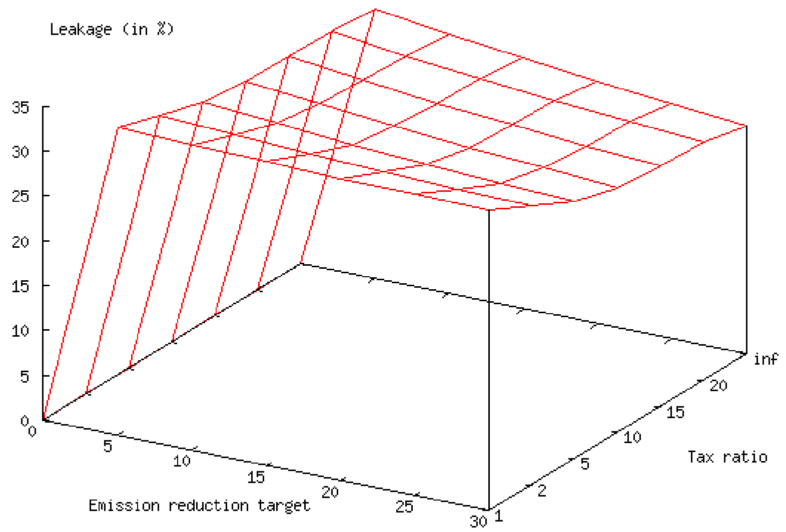
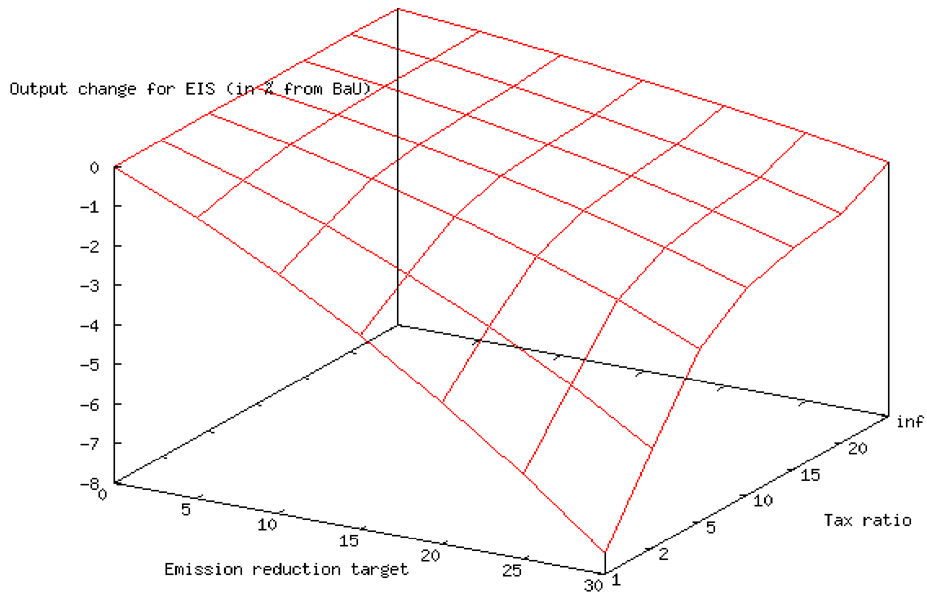


Figure 3: Changes in sectoral production of EU industries

a. Energy-intensive industries (EIS)



b. Mineral oil industries (OIL)

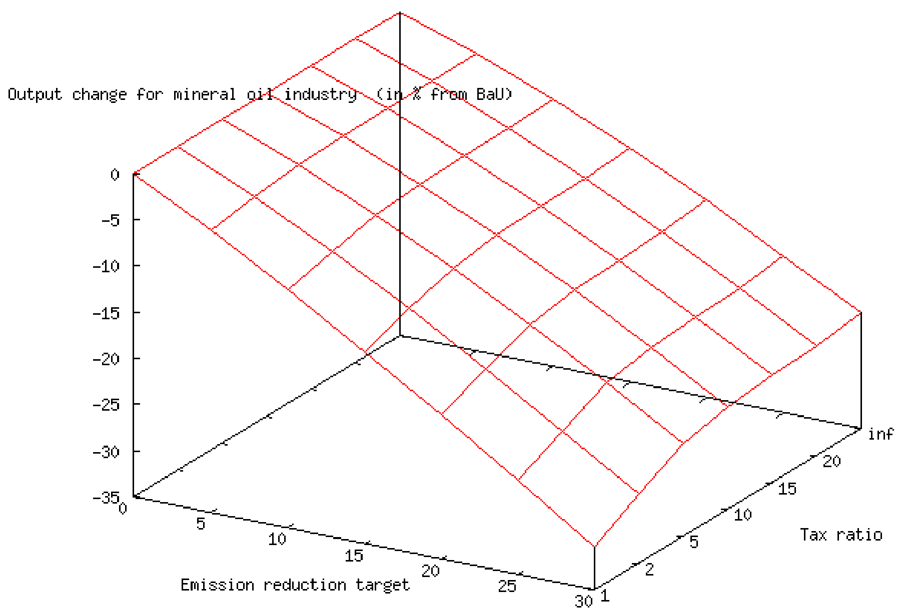


Figure 3: Changes in sectoral production of EU industries

c. Other industries and services (OTH)

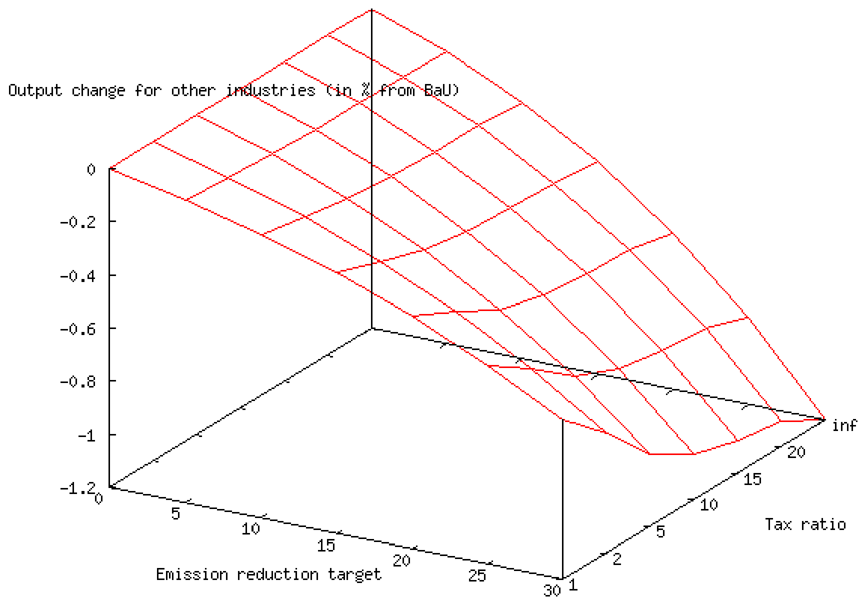
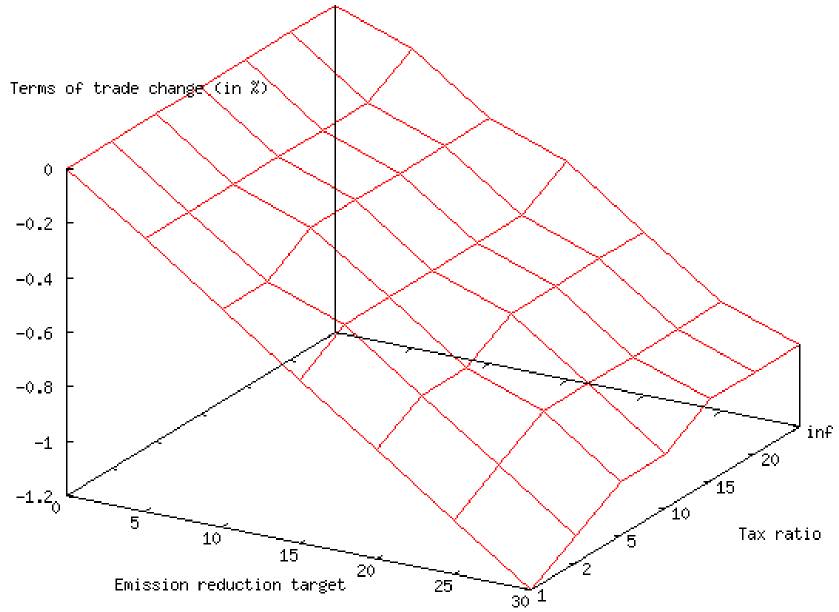


Figure 4: Changes in EU competitiveness at the national and sectoral level (in % from BaU)

a. Terms of trade (in %)



b. Energy-intensive industries (EIS) – RCA (in %from Bau)

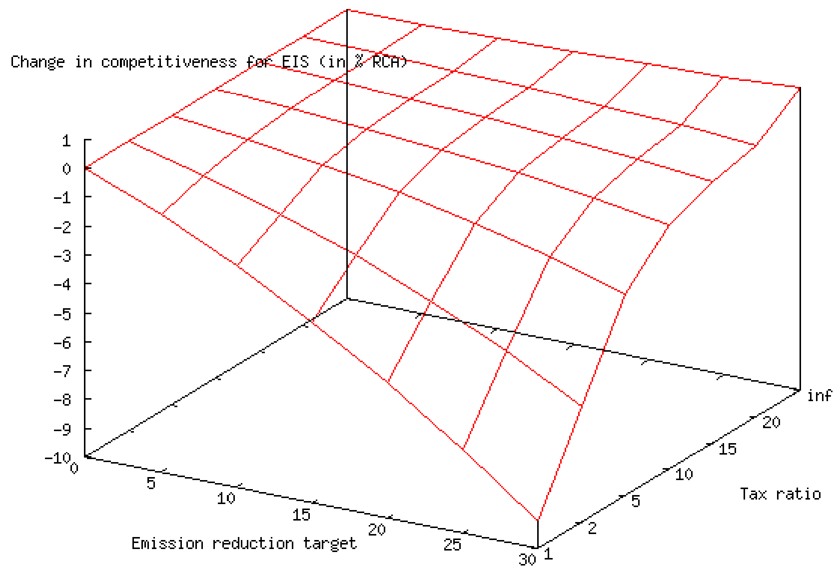
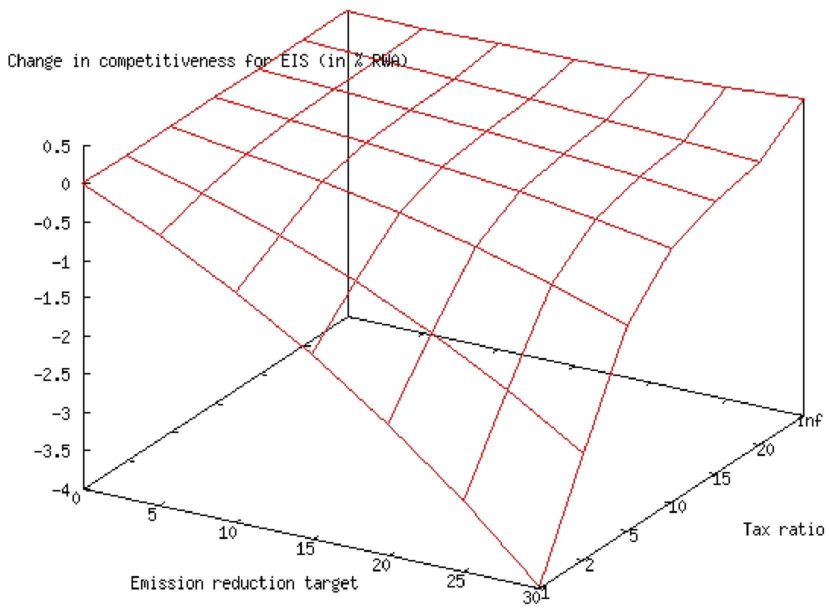


Figure 4: Changes in EU competitiveness at national and sectoral level (in % from BaU)

c. Energy-intensive industries (EIS) – RWS (in %from Bau)



d. Energy-intensive industries (EIS) – RTB (in %from Bau)

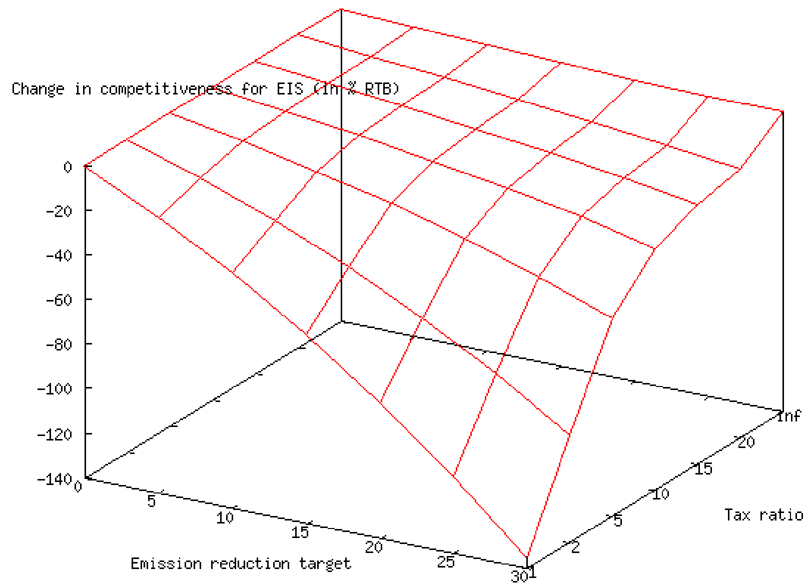
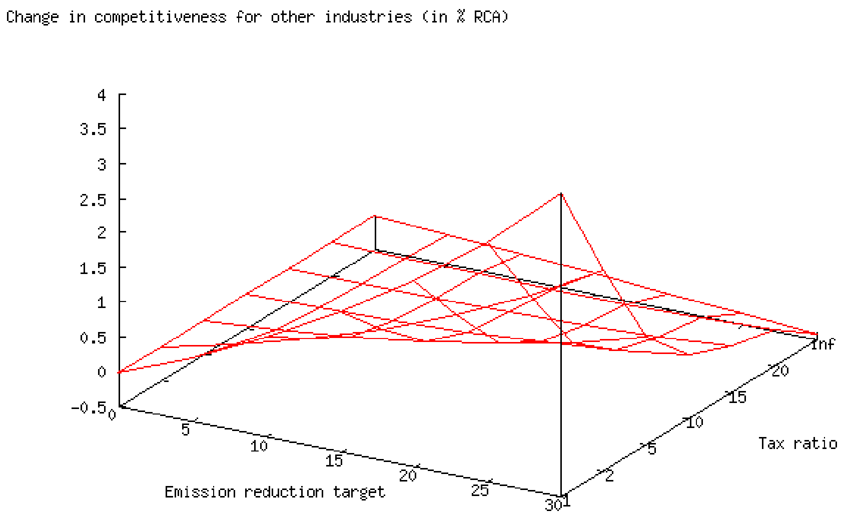


Figure 4: Changes in EU competitiveness at the national and sectoral level (in % from BaU)

e. Other industries and services (OTH) – RCA (in %from Bau)



f. Other industries and services (OTH) – RWA (in %from Bau)

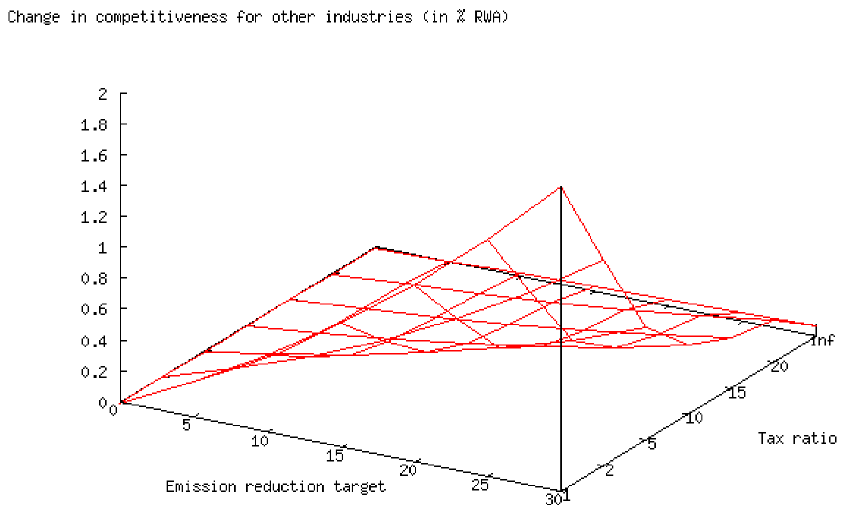


Figure 4: Changes in EU competitiveness at the national and sectoral level (in % from BaU)

h. Other industries and services (OTH) –RTB (in %from Bau)

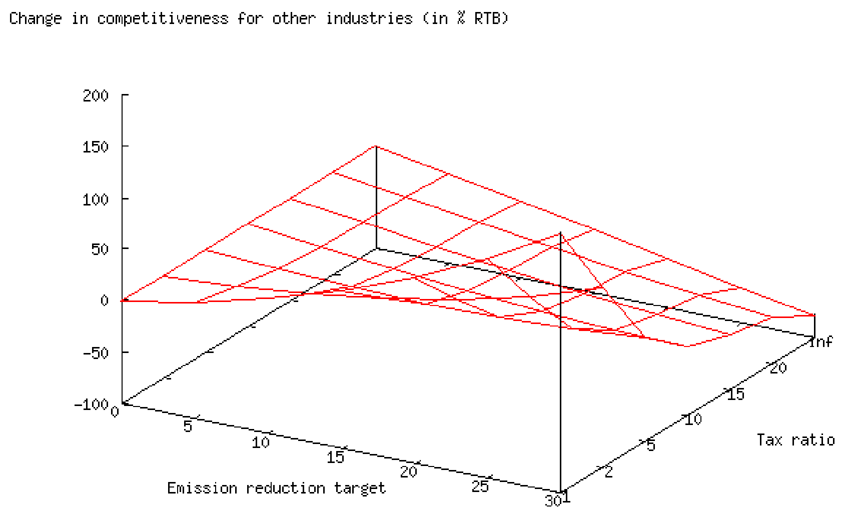
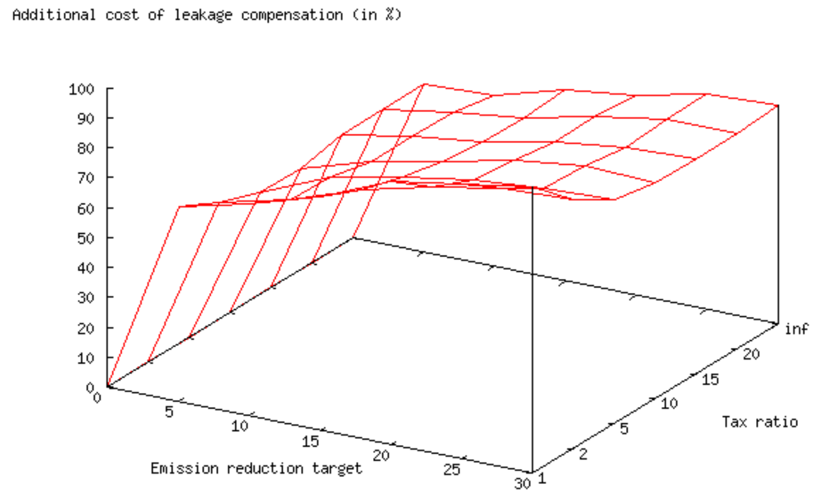


Figure 5: Cost implications of unilateral carbon restrictions for the EU

a. Additional cost of leakage compensation (in % of cost without leakage compensation)



b. Cost of tax differentiation without leakage compensation (base: uniform taxation)

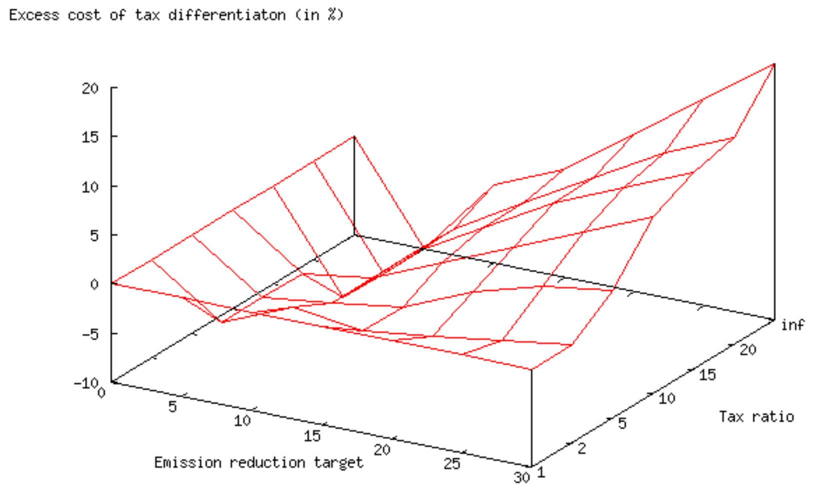


Figure 5: Cost implications of unilateral carbon restrictions for the EU

c. Cost of tax differentiation with leakage compensation (base: uniform taxation)