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D6.1 Report on effects of different sustainability indicators on competitiveness

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Abstract

The European Union committed itself to achieve unilaterally at least a 20% reduction in its greenhouse gas emissions by 2020 compared to the 1990 level. We investigate the implications of alternative EU emissions pricing strategies on economy-wide adjustment costs and competitiveness. In dealing with competitiveness, our approach is to combine normative economics and a descriptive tool (indicators) analysis. The quantitative assessment demonstrates that competitiveness effects at sectoral level are highly sensitive to the particular indicator chosen but we find a considerable consistency among alternative indicators as binary measures. In terms of conventional trade theory, the EU has a comparative advantage in the energy-intensive industries which is decreased, but not abolished, even if relatively stringent emissions reduction targets and a uniform tax implementation apply. This outcome makes differential emissions pricing redundant as it leads to the pending trade-off between sector-specific competitiveness concerns and broader economic efficiency considerations. We conclude that a general-equilibrium perspective is essential to assess competitiveness implications resulting from any policy interference.

JEL Classification: D58, H21, H22, Q48

Keywords: EU climate policy, unilateral emissions reduction, competitiveness indicators

Non-Technical Summary

This paper demonstrates the extent and limitations to which trade-based competitiveness concepts (indicators) at sectoral and national level can introduce an ‘operational element’ into the current discussions on EU leadership in GHG emission reduction. Employing a set of appropriate competitiveness indicators in the multi-sector, multi-region model for the world economy, we investigate the implications of alternative emissions pricing strategies under stringent unilateral carbon emissions regulation on economy-wide adjustment costs and competitiveness in the EU. From the methodological perspective, we find that the use of comparative advantage indicators within this framework can add to our understanding of changes in trade patterns in different industries, an issue that is of immense importance to the European policy makers. For a balanced view on competitiveness, it is, however, important to account for changes across the various sectors of the domestic economy rather than to focus 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. Our analysis warrants the careful and complementary use of macroeconomic and competitiveness indicators: Results based on any (sectoral) competitiveness indicator as a cardinal measure are highly sensitive to the particular indicator chosen but we find a considerable consistency among alternative indicators as a binary measure.

Overview

To kick-start ambitious global actions on climate change as the guiding principle for the Post-Kyoto architecture, the European Union (EU) agreed to take the lead and to achieve unilaterally at least a 20% reduction of greenhouse gas (GHG) emissions by 2020 compared to the 1990 level. Under the condition that other major emitting countries commit themselves to comparable actions under a Post-Kyoto global climate agreement, the EU offered to increase its emissions reduction target to 30%. International climate change negotiations in Copenhagen in December 2009 resulted, however, in a voluntary agreement which failed to pledge emissions cuts sufficient to achieve the objective of limiting the global average temperature increase to no more than 2°C above pre-industrial levels. Given deep divergences between developed and developing countries, and the weak pledges made by major non-European industrialised emitters, the outcome of the climate talks in Copenhagen suggests that the EU leadership in GHG emissions reduction might prevail not only by 2020, but possibly even beyond this time horizon. More recently, Spencer et al. (2010) argued that there might be a case for the EU to expand the leadership and to move unilaterally to a 30% reduction in order to rebuild trust and credibility with developing economies and to strengthen the political space in industrialised countries such as Australia and the USA.

Ambitious climate change policy has, however, repercussions for the EU objective of increasing competitiveness, economic growth and enhancing job creation alongside the Lisbon Strategy (EU, 2006). Stringent environmental policies raise concerns on competitiveness, particularly to those sectors which are energy-intensive, export-oriented and not covered by globally harmonised policies, but which are a subject to unilateral actions. The political debate in the EU has therefore centred around the possible adverse implications of stringent environmental policy on the manufacturing industry. Concerns about competitiveness have become the 'leitmotiv' in the design of climate change policy in the European Union[1].

There is broad literature available on environment-competitiveness linkages both at sectoral and at economy-wide level. Both strands of literature exhibit shortcomings with respect to the consistent and coherent analysis of competitiveness. Sectoral studies discuss competitiveness impacts in a quite narrow (partial) perspective with a focus on those industries directly affected by a respective regulation (Jaffe et al., 1995; Xu, 1999; Huybers and Bennet, 2003; Demaillya and Quirion, 2008).

In the multi-regional multi-sectoral studies the potential impacts of environmental regulation on InEuropean competitiveness have been studied among others by Bollen et al. (2003), Klepper and

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[1] Focusing on the "pressing challenge for competitiveness", the President of the European Council H. van Rompuy has recently suggested to regularly monitoring competitiveness developments in the EU on the basis of selected competitiveness indicators. This new element in the EU's drive for competitiveness is expected to

Peterson (2004), Böhringer and Lange (2005), Alexeeva-Talebi et al. (2008). Neither of these studies investigates all relevant trade-offs pertaining competitiveness and explicitly connects the (economy-wide) competitiveness implications with the normative concept of welfare.

This paper demonstrates the extent and the limitations to which competitiveness concepts at sectoral and economy-wide level can introduce an 'operational element' into the current discussions on the EU leadership in GHG emissions reduction. From the methodological perspective, the overall objective is to assess competitiveness implications combining normative economics and a descriptive tool (indicators) analysis. Our paper complements research on competitiveness impacts of climate policies in a threefold manner: Firstly, a thorough analysis of competitiveness implications requires a clear-cut notion of competitiveness and precise specification of appropriate indicators: An issue which cannot be clearly measured will be difficult to improve. In the past, the discourse on competitiveness has been exacerbated by an extraordinary variety of notions and measurement concepts. We therefore review the most recent literature on competitiveness concepts, identify key dimensions of competitiveness notions and specify appropriate indicators at sectoral and economy-wide level. Our focus is on identifying what might be considered as a consensus in the literature rather than on covering all possible dimensions and indicators. Secondly, we implement selected competitiveness indicators into a multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy thereby accommodating the consistent assessment of potential trade-offs between sectoral competitiveness impacts and overall efficiency effects triggered by policy interference (Böhringer and Welsch, 2006). Recent empirical contributions on competitiveness are highly relying on revealed comparative advantage (RCA) indicators (Fertö and Hubbard, 2003; Cai and Leung, 2008; Frantzen, 2008). In order to demonstrate how these indicators can be operationalised within a CGE framework and to test the consistency of alternative indicators, we perform an impact analysis of EU leadership in climate policy. In advocating the use of the revealed comparative advantage indicators, Webster (1991) argues that "it must […] be a desirable property of any measure of RCA that it reflects equilibrium trade flows and is not influenced by disequilibrium at the macroeconomic level". Our methodological approach establishes this property. Moreover, the CGE framework allows minimising the biasness of the RCA measures due to the potential trade data inconsistency, nominal exchange rate impacts and inflation shocks. Among others, Sorsa (1994) argues that caution is required when concluding that changes in trade patterns result from environmental regulation. Our framework, however, allows linking changes in comparative advantage directly to a policy intervention. Thirdly, there are a number of plausible arguments signalling that the link between competitiveness and welfare could be significant. We therefore go

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provide an early detection of possible divergences between the Member States and timely policy reactions (EU, 2010).

beyond a purely descriptive assessment of competitiveness through an *explicit* link to the normative concept of welfare underlying the microeconomic foundations of economy-wide CGE analysis. Moreover, given the fact that competitiveness can be meaningfully defined at both sectoral and economy-wide level, we argue that the analysis of the interdependences between both dimensions would provide a more coherent approach to this phenomenon.

While computable general equilibrium models can incorporate key competitiveness and macroeconomic indicators in a single micro-consistent framework, the empirical contribution of this paper reveals the problems to be faced when competitiveness is prioritised by policy makers. Our quantitative assessment of alternative EU compliance strategies to unilateral emissions reduction targets discloses the pending trade-off between sector-specific competitiveness concerns and broader economic efficiency considerations: Differential emissions pricing may improve competitiveness of favoured industries (measured by alternative versions of comparative advantage indicators) and economy-wide competitiveness (measured by ToT). The latter effect has important welfare implications for the design of the carbon abatement policies (Böhringer and Rutherford, 2002 and Böhringer et al., 2009). The welfare improvements due to increasing ToT in our simulations are, however, not of such an order of magnitude to offset the domestic adjustment costs which result from foregone cheap abatement options in the carbon-intensive segments of the economy. Hence, differential emissions pricing may improve competitiveness of favoured industries and economy-wide competitiveness but will inevitably induce economy-wide excess costs compared to uniform emissions pricing.

The remainder of this paper is structured as follows: Section 2 reviews competitiveness concepts and discusses selected competitiveness indicators that are subsequently implemented into a computable general equilibrium model. Section 3 provides a CGE-based policy assessment of unilateral EU climate policies. Section 4 concludes the paper.

1. Competitiveness Indicators

1.1.Notions of Competitiveness

When dealing with competitiveness, the first major methodological problem refers to the lack of well-defined conceptual framework: Competitiveness is not a subject category per se, neither in economic theory in general nor in normative economics in particular. Despite an increased attention over the past decades and an abundance of literature, the notion of sectoral and national competitiveness has remained rather susceptible for ambiguities. Remarkable diversity of the competitiveness concepts which have been elaborated in the last two decades in economic literature reflects the multidimensional nature of this phenomenon.

The second major methodological problem refers to the operationalisation of the competitiveness concept(s) for a quantitative policy analysis. A review of existing literature yields an impressive array of alternative measurement concepts. However, the choice of competitiveness indicators is often insufficiently transparent or even arbitrary. Competitiveness determinants are frequently labelled as competitiveness indicators and therefore just purporting to measure competitiveness. More recently, several studies stressed the importance of distinguishing between *competitiveness indicators* which describe the outcome of competitiveness and *competitiveness determinants* which govern the ability to compete (Reichel, 2002; Aiginger, 2006).

In order to adequately address this requirement, we briefly elaborate on its conceptual underpinning: A variety of factors (determinants) govern competitiveness which is obviously an unobservable variable –otherwise we could easily measure it. In principle, all relevant factors determining competitiveness need to be considered. But ultimately, the choice of determinants will depend on a theory specifying the relationship between observable determinants and competitiveness. The outcome of competitiveness is, however, reflected in observable outcome (result) variables involving e.g. international trade performance or profitability (see below). These outcome variables may be used to construct a variety of competitiveness indicators. Thus, although competitiveness appears not to be precisely measurable, the underlying assumption is that competitiveness indicators may be used to disclose the corresponding ability to compete.

Based on most recent literature review, the next sections 2.1.1 and 2.1.2 identify key dimensions in the *outcome-based competitiveness notion(s)* at sectoral and national level and specify appropriate measurement concepts (i.e. competitiveness indicators)[2]. Given the multidimensional nature of competitiveness, the purpose of these sections is to detect what the consensus is in literature rather than to cover all relevant dimensions and indicators of competitiveness.

1.1.1 Competitiveness at sectoral level

Focusing on the outcome-based notion, much agreement in literature exists on two key dimensions of sectoral competitiveness: "*ability to sell in international markets*" and "*ability to be profitable*".

The most widely accepted definition of sectoral competitiveness refers to the ability of an industry or a sector to succeed in international markets (Jaffe et al., 1995; Jenkins, 1998; Xu, 2000; Klepper and Peterson, 2003; Babool and Reed, 2009). International competitiveness, defined in terms of foreign

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[2] This implies that we skip the discussion on the determinants of competitiveness.

trade performance, is thereby deeply encroached with theory of international trade in general and comparative advantage in particular. According to the theory of comparative advantage, countries are likely to export those goods and services in which they have a comparative cost advantage. Recently, the concept of revealed comparative advantage has been increasingly interpreted as “revealed *competitive* advantage”, while industries with a comparative advantage have been considered as internationally competitive (Peterson, 1988; Jenkins, 1998; Fertö and Hubbard, 2003; Ahrend et al., 2007; Cai and Leung, 2008).

The underlying rationale for that is the interest in relative differences in international cost structure of competing industries that is common in literature on comparative advantage and competitiveness.

The second dimension in the outcome-based notion of sectoral competitiveness is referred to in Sell (1991), EU (2005) and analysed by Demailly and Quirion (2006, 2008), Smale et al. (2006), Sato et al. (2007) and Demailly et al. (2007) in the context of the EU Emissions Trading Scheme (EU ETS). This dimension refers to the sectoral “ability to earn”, i.e. the capacity to sell profitably in national and international markets. Cost pressure may not be (immediately) reflected in increasing prices, while profits could play a buffer role to keep the market shares constant. According to this strand of literature, impacts on profitability have to be taken into consideration when the implications on competitiveness at sectoral level are measured. Demailly and Quirion (2006) stress the importance to disentangle the implications of policy on both dimensions of sectoral competitiveness “ability to sell in international markets” and “ability to be profitable”.

Table **1** provides a selection of competitiveness indicators which can be used to quantify specific aspects of competitiveness presented above. A relatively narrow range of indicators appears to be directly relevant when competitiveness indicators (and not competitiveness determinants) are considered. International trade performance is basically evaluated by two types of indicators: those based on trade data only and those based on a combination of trade and production (consumption) data[3]. However, the latter type of competitiveness indicators – in Table 1 represented by ratio of exports (imports) to production (consumption) – is rarely used in empirical studies due to the lack of consistency (Reichel, 2002). In contrast to international trade performance, the construction of an appropriate indicator to measure profitability appears to be difficult as this measure is typically related to the company’s level and as the data availability is restricted (EU, 2005). Harvey (2003) distinguishes between three types of profitability indicators that might be constructed at industrial level using

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[3] We do not consider the indices adopting a probabilistic framework in which revealed comparative advantage indicators are expressed in terms of the deviation between actual and expected levels of trade, production and consumption (Ballance, 1988).

national accounts data: profit margin (profit over output), rates of return (profit over capital stock), and profit shares (profit over total factor income). In Table 1 gross operating rate and EBITDA belong to the first type of profitability indicators.

Table 1: List of competitiveness indicators at sectoral level[4]

International trade performance	Profitability performance
• **Indexes of revealed comparative advantage**[5] Balassa (1965), Ballance et al. (1987), Gorton et al. (2000)*, Fertö and Hubbara (2003)*, Abidin and Loke (2008)*,	• **Earnings before interests, tax, debt and amortization (EBITDA)** Smale et al. (2006)*, Sato et al. (2007)*, Demaillya and Quirion (2006, 2008)*
• **Export (import) ratio in world's total exports (imports)** Kravis and Lipsey (1992)*, Carlin et al. (2001), Reichel (2002)*	• **Gross operating rate** EU (2005), Peltonen et al. (2008), EU (2008)
• **Constant market share index** Koopmann and Langer (1988)*, Holst and Weiss (2004)	• **Rate of return** Rossi et al. (1980)*, Wang (1995), Manne and Barreto (2004)
• **Intra-industry trade index (Grubel-Lloyd)** EU (2005)*, Havrila and Gunawardana (2003)*	• **Profit share** Torrini (2005)
• **Ratio of exports (imports) to production (consumption)** Ballance et al. (1987), Peterson (1988)	

1.1.2 Competitiveness at national level

For more than two decades, the concept of competitiveness at national level has been discussed rather controversially: Paul Krugman, one of the most prominent members of the scientific community, argued that „competitiveness is a meaningless word when applied to national economies" (Krugman, 1994)[6].

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[4] We mark the studies with asterisk "*" when they explicitly refer to the competitiveness concepts.

[5] There are several versions of trade-based measures, including normalised net export indicators (see below).

[6] More recently, Krugman seems to tone down his criticism. In his commentary "The Making of a Euromess" (The New York Times, February 2010) Krugman elucidates the reasons behind the economic crisis in Spain and potential remedies. He argues, in particular, that Spain cannot regain its competitiveness losses fast due to the strongly raising costs and prices that country has been experiencing during the economic recovery. But if the Euro had not been introduced, Spain could have done it easily by devaluating the peseta.

In contrary to such fundamental criticism, alternative concepts of competitiveness at national level are widely used in scientific and non-scientific contributions[7] since Porter (1990) drew attention to this phenomenon. The surveys of alternative notions of competitiveness at economy-wide level can be found for example in Reichel (2002), Aiginger (2006) and Siggel (2007). Despite an impressive variety of competing definitions, considerable support exists for the interpretation of national competitiveness which is in line with its counterpart at the sectoral level, albeit this notion is subject to ambiguity: Targeting the result-oriented notion, there are basically two main ways how competitiveness at national level is discussed in literature: The traditional approach identifies countries' international trade performance ("ability to sell") as the key dimension (Durand and Giorno, 1987; Nielsen et al. , 1995). More recently, the ECB (2009) referred to this notion as a nucleus when dealing with competiveness at economy-wide level. The empirical studies in this strand of the literature analyse the impact of the driving forces behind countries' increasing (decreasing) competitiveness (see for example Fagerberg, 1988). However, the paradigm defining competitiveness at national level has been shifting in the most recent contributions, away from the "ability to sell" towards a concept which is in line with normative economics. This strand of literature makes the point that the focus on international trade might be misplaced if it represents only a small fraction of the GDP, while increasing export activities is not the ultimate goal of a nation. The expansion of exports might come from low wages, subsidies or a weak currency resulting in lower standards of living in the country. The real matter then becomes "the ability to earn", i.e. the ability to create wealth or high standard of living as a central dimension of national competitiveness (Jenkins, 1998; EU, 2004; Grilo and Koopman, 2006; Aiginger, 2006). Grilo and Koopman (2006) argue that international trade performance pertains to sectoral level only, while improving competitiveness at the national level implies enhancing welfare for the citizens of a country. According to this study, GDP per capita might be used as a proxy to measure welfare empirically. The authors also plead for the use of this indicator not as an ordinary measure,

but to use the performance of a particular country as a benchmark for possible improvements. Dollar and Wolff (1993), Auerbach (1996), Reichel (2002), Hildebrandt and Silgoner (2007) and ECB (2009) take an intermediate position referring to both "ability to sell" and "ability to earn". The latter view supposes that changes in competitiveness at economy-wide level measured by international performance indicators shall not be interpreted in isolation, but rather against the background of a country's economic development and/or standards of living. This basically implies that the rise in

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[7] In the globalised world, policy makers have been increasingly concerned about the ranking national level of competitiveness against other countries' performance (see for example studies published by World Economic Forum and World Bank, respectively: Global Competitiveness Report 2009-2010 and Doing Business Report). A number of critical contributions have been made to this approach.

living standards can be attributed to increasing competitiveness at national level as measured by the international trade performance indicators.

Table 2 provides a selection of competitiveness indicators at national level according to the two key dimensions presented above. They have been found in both empirical and theoretical papers. Obviously, the same indicators may be used to assess competitiveness at sectoral and economy-wide levels. This is particularly true when assessment of the international trade performance is required (for example using export market shares). Among others, Hildebrandt and Silgoner (2007) and ECB (2009) employ a variety of indicators to measure the international dimension of a country's competitiveness such as export growth, exchange rate, balance of trade, terms of trade and market share. While the latter set of indicators might be calculated for both large and small open economies, other indicators might be meaningfully employed for a particular type of economy only. For example, the ToT indicator is not applicable for measuring competitiveness of a small open economy with terms of trade set by world markets.

Table 2: List of competitiveness indicators at the national level[8]

International trade performance	"Ability to earn"/ "Ability to create welfare"
• **Trade balance** (Current account) Robison (1988), Nielsen et al. (1995)*, Duval and Hamilton (2002), Deutsche Bundesbank (2007)*, Zemanek et al. (2009)*	• **GDP per capita** Grilo and Koopman (2006)*
• **Terms of trade** Riley, (1980)*, Di Bartolomeo (2005)*, Hildebrandt and Silgoner (2007)*	• **(Labour-) productivity** Temple and Urga (1997)* , OECD (2001)
• **(Real) exchange rate** Bovenberg (1989)*, Lipschitz and McDonald (1992), Vitek (2009)*	
• **Export market share** Fagerberg (1988)*, Amable and Verspagen (1995), ECB (2005)*, Danninger and Joutz (2007)	

We conclude at this stage that competitiveness can be meaningfully defined at both sectoral and economy-wide level, while the analysis of the interdependences between both dimensions on the

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[8] See footnote 3.

basis of selected indicators would provide a more coherent approach to this phenomenon. In general, there is no specific quantitative tool that encompasses all features for comprehensive competitiveness analysis at sectoral and national level, but rather a set of models. Computable general equilibrium models can thereby incorporate several key competitiveness indicators in a single micro-consistent framework, allowing for a systematic trade-off analysis alongside the notion of competitiveness presented above. While a CGE model provides an open framework for linkages to sector-specific models (to study impacts on sectoral profitability), this paper tries to make a good case for the use of standard computable general equilibrium model to analyse the independences between international-trade dimension of competitiveness at sectoral and economy-wide level and to establish a link between the latter and the normative welfare analysis.

The overall conclusion which can be drawn from literature on competitiveness indicators to measure international trade performance is that it is not possible to identify a valid measure from a theoretical (including normative) and empirical perspective. This is in particular true for sectoral competitiveness indicators. Since revealed comparative advantage indicators are by far the most widely employed measures (for alternative versions see Vollrath, 1991), we employ three indicators which are most common in empirical literature varying reference points of comparison (see subsequent section) and test their consistency. Although unilateral climate policy will have an impact on trade patterns and comparative advantage indicators, other influences such as changing terms of trade make it impossible to determine what portion of the shifts in comparative advantage can be directly attributed to additional abatement costs (see Robison 1988). Choosing the terms of trade (ToT) indicator to measure competitiveness at the economy-wide level allows us therefore not only to analyse the independences between sectoral and economy-wide level of competitiveness but also to establish links to the normative concept of welfare. Thereby, GDP per capita and labour productivity as proxies for economy-wide ability to create welfare are incorporated in the core CGE model (Böhringer and Löschel, 2006). However, the normative welfare analysis in a computable general equilibrium framework is based on a more sound theoretical measure such as the Hicksian equivalent variation which is used in our framework.

1.2. Selected Competitiveness Indicators for CGE-Analysis

In our numerical analysis, we focus on the international dimension of competitiveness at the economy-wide and sectoral level. To investigate the implications of EU leadership in climate policy on economy-wide competitiveness of a large open economy we employ the terms of trade indicator in a multi-sectoral model following Ølgaard (1981) as:

$$ToT_i = \frac{\sum_j P_{ij}^x X_{ij}}{\sum_j P_{ij}^m M_{ij}} \qquad (1)$$

X denoting export quantities, P^x export prices*,* P^m import prices, *M* import quantities, *i* the region and *j* the sector. This index compares the ratio of a country's overall exports with the ratio of country's overall imports in all sectors. Terms of trade are said to deteriorate if the indicator decreases; terms of trade are said to improve if the indicator increases.

Among sectoral indicators which reveal comparative advantage, the Relative World Trade Shares (RWS) indicator, being proposed by Balassa (1965), is the most widely used trade-based measure[9]. Letting *X* denote exports, P^x export prices, *i* the region and *j* the sector, the RWS index for region *i* in sector *j* can be written as follows:

$$RWS_{ij} = \frac{P_{ij}^x X_{ij} / \sum_i P_{ij}^x X_{ij}}{\sum_j P_{ij}^x X_{ij} / \sum_i \sum_j P_{ij}^x X_{ij}} \qquad (2)$$

This index compares the ratio of a country's exports in a certain sector to the world's exports in this sector with the ratio of country's overall exports to the world's exports in all sectors. If the sectoral export-import ratio is identical to the economy-wide ratio, the RCA index takes the neutral value of one ($RWS_{ij} = 1$). Thus, a region *i* is said to have a comparative advantage in sector *j* if the RWS index exceeds unity ($1 < RWS_{ij} \leq \infty$). By contrast, a region *i* has a comparative disadvantage in sector *j* if the RWS index takes the values between zero and one ($0 \leq RWS_{ij} < 1$). The lack of symmetry between the value ranges for comparative advantage ($1 < RWS_{ij} \leq \infty$) and comparative disadvantage ($0 \leq RWS_{ij} < 1$) is considered to be one of the major shortages in this index definition.

The previous version of a sectoral indicator has been also criticised because the import flows are not taken into consideration. We therefore consider an alternative (highly policy relevant) sectoral competitiveness indicator based on Balassa (1965). The Revealed Comparative Advantage (RCA) index is concerned with the competitiveness of different industries within an economy. Letting *X*

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[9] The sectoral measures presented in (2), (3) and (4) belong to the type of revealed comparative advantage indicators. For convenience, we hereafter will refer to (2) as the Relative World Trade Share (RWS) indicator and to (4) as the Relative Trade Balance (RTB) since these notations are also common.

denote exports, P^x export prices, P^m import prices, *M* imports, *i* the region and *j* the sector, the RCA index for region *i* in sector *j* can be presented as follows:

$$RCA_{ij} = \frac{P_{ij}^x X_{ij} / P_{ij}^m M_{ij}}{\sum_j P_{ij}^x X_{ij} / \sum_j P_{ij}^m M_{ij}} \tag{3}$$

For a particular region and sector, this index compares the ratio of exports by a specific sector to its imports with the ratio of exports to imports across all sectors of the region. The RCA indicator has the same value range as the RWS index ($0 \leq RCA_{ij} \leq \infty$) and thus may be interpreted regarding the range for comparative advantage and disadvantage in a similar way as the previous indicator. Finally, we refer to the 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 (Balassa, 1989):

$$RTB_{ij} = \frac{P_{ij}^x X_{ij} - P_{ij}^m M_{ij}}{P_{ij}^x X_{ij} + P_{ij}^m M_{ij}} \tag{4}$$

This index has the neutral value of zero ($RTB_{ij} = 0$) and the value range of $-1 \leq RTB_{ij} \leq 1$. The region *i* is said to have a comparative advantage in sector *j* if the RTB index exceeds zero; comparative disadvantage exists for values less than zero.

There is a range of slightly different measures and normalisation approaches for the mentioned indicators (see Reichel, 2002, for a comprehensive review) but in this analysis we stick to the versions indicated above. The selected sectoral indicators thereby vary with respect to the point of reference: The first indicator (RWS) shows how the relative performance of a particular sector changes compared to the relative performance of the same sectors across the world. The second indicator (RCA) compares the performance of a particular sector with an average performance of all sectors within the same region. Finally, changes in the third indicator (RTB) show how net exports of a particular sector varies relative to the sum of exports and imports in the same sector[10]. While all three versions of sectoral indicators purport to measure comparative advantage of a particular industry, the consistency in the performance shall be analysed.

From the partial equilibrium perspective it is straightforward to show that increases in exports X_{i1} in the region *i* and the sector *1* result *ceteris paribus* in increasing competitiveness according to RTB_{ij}, RCA_{ij} and RWS_{ij} indicators. Vice verse, increasing imports will *ceteris paribus* decrease sectoral competitiveness. The partial equilibrium setup ignores, however, the interactions with the rest of economy and the world which might have important implications for the value of the indicator. In the next section, the stylised general-equilibrium framework based on the standard trade theory is employed to irradiate some basic relationships between competitiveness indicators and welfare.

1.3. Assessing linkages between competitiveness and welfare

Conventional theory suggests that improvement in the international terms of trade increases welfare, a proposition that was analytically proved by Krueger and Sonnenschein (1967) for perfectly competitive world with no distortions. Employing a numerical framework, Böhringer and Rutherford (2002) and Böhringer et al. (2009) have recently developed a technique which allows decomposing the total welfare effects of carbon abatement policies into primary domestic market effect (at constant international prices) and a secondary international spillover impact as a result of changes in international prices (ToT). Figure 1 provides the basic arguments behind demonstrating that changes in competitiveness at economy-wide level (if measured by ToT) can be directly linked to the normative concept of welfare. For illustrative purposes we employ a standard general-equilibrium trade model in which each country produces two goods y_1 and y_2. In the initial equilibrium, country A produces at point S, where the smooth production possibility frontier TT is tangent to the isovalue line with the slope tgα - the latter is equal to minus the relative price of good y_1 P_1/P_2. The country consumes at point N (d_1^*, d_2^*) such that the quantity of the good x_1^* is exported and m_2^* is imported. Now consider what happens when production possibility frontier TT shifts to $T'T'$ which might be due to the environmental tax levy on the production of the "dirty" good y_1 resulting in efficiency losses. The economy's production shifts from S (y_1^*, y_2^*) to D ($\hat{y}_1, \hat{y}_2$) and consumption choice from N (d_1^*, d_2^*) to U ($\hat{d}_1, \hat{d}_2$) if terms of trade are fixed (tgα). The economy moves to lower indifference curve and is worse off since the efficiency losses in production result in decreasing welfare. The impact on the latter can be proxied by the equivalent variation (EV) which measures how much money has to be taken away from the consumer before imposing the environmental tax in order to leave him as well off as he would be after.

In geometric terms, the adverse impact on welfare, as measured by the EV, is given by PR. Loosening the assumption of a small open economy now, we suppose that country A can reduce the worldwide supply of y_1 relative to y_2 such that its terms of trade improve. The new relative price of good y_1 P_1/P_2 has the slope tgβ. The new consumption bundle moves from U to T which is consistent with the same level of production as under U (D ($\hat{y}_1, \hat{y}_2$). At sectoral level, the economy

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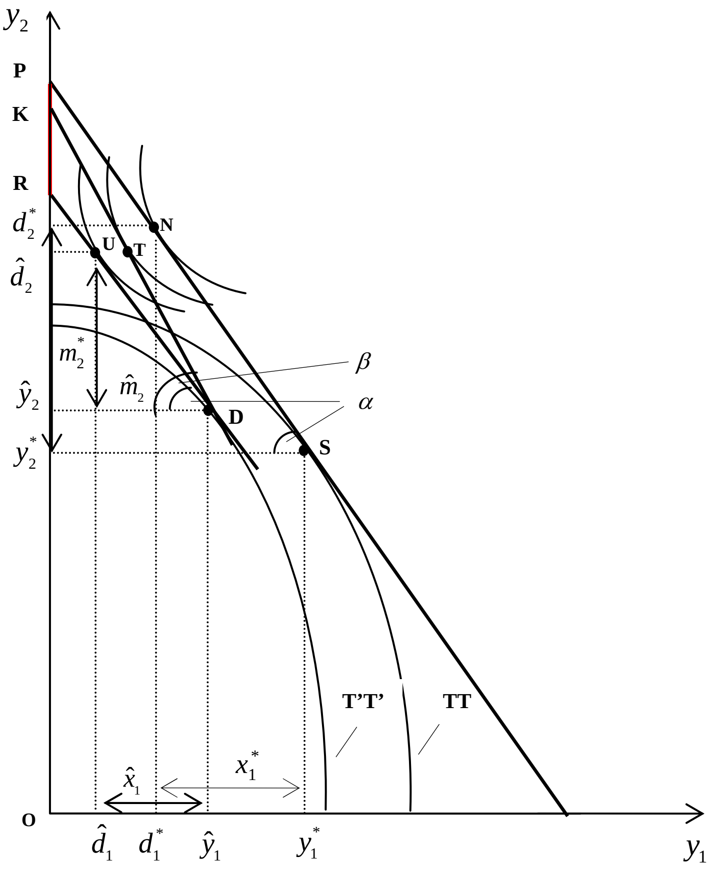
[10] This is in particular true for two first indicators. The third one is less common in the empirical research but

can now sell less exports (expanding the domestic consumption) in sector 1 and import more goods from abroad in sector 2. Increasing terms of trade in Figure 1 reduces welfare losses from *PR* to PK. The decomposition procedure reveals the extent to which domestic costs decrease as a result of the impact of carbon abatement on terms of trade.

Figure 1: Impact of increasing competitiveness on welfare (equivalent variation)



While changing terms of trade has an impact on sectoral export and import level, it is easy to show that these adjustments cannot be captured by sectoral indicators RWS, RCA and RTB as long as we assume the extreme case of the asymmetric trade as in Figure 1. That is: only sector 1 exports produced goods $M_{i1} = 0$ and $X_{i1} \neq 0$, while imports flow to the sector 2 only such that $X_{i2} = 0$ and $M_{i2} \neq 0$. Albeit all sectoral indicators are defined for these special cases ($-1 \leq RTB_{ij} \leq 1$, $0 \leq RWS \leq \infty$ and $0 \leq RCA_{ij} \leq \infty$), the sectoral indicators take the values $RTB_{i1} = 1$, $RWS_{i1,} \xrightarrow{M_{i1} \to 0} \infty$ and $RCA_{i1} \xrightarrow{M_{i1} \to 0} \infty$ for all levels X_{i1}, as long as the sector 1 does not import any goods from abroad (i.e. $M_{i1} = 0$). For sector 2, the indicators amount to $RTB_{i2} = -1$, $RWS_{i2} = 0$ and $RCA_{i2} = 0$ for all levels of M_{i2}, respectively. Obviously, constant RTB_{ij}, RCA_{ij} and

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has a more sound theoretical foundation (Deardorff, 1980).

RWS_{ij} at sectoral level cannot under these assumptions capture changes in competitiveness and might be consistent with different levels of ToT and welfare (i.e. monotonic transformation is not possible).

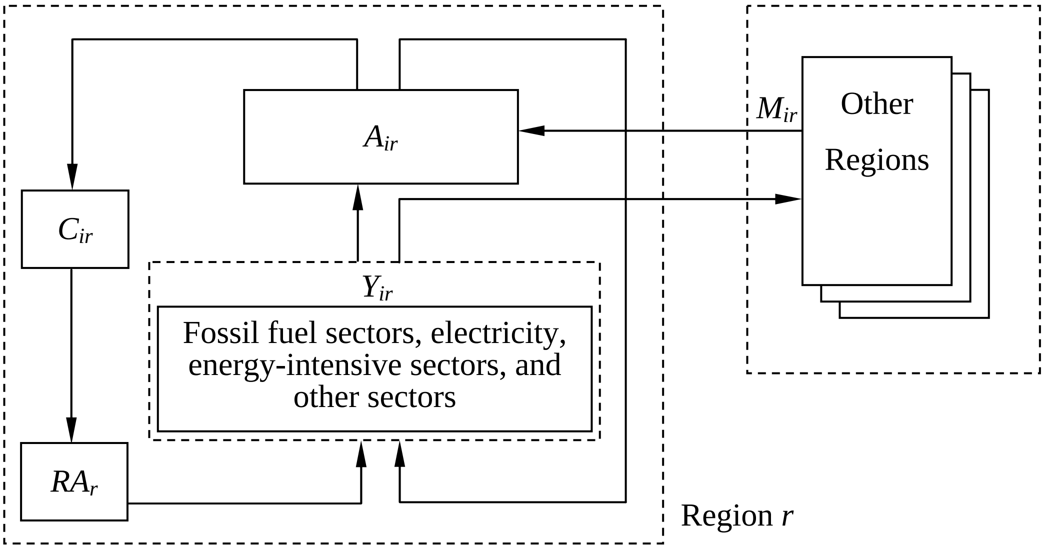
Hence, using a standard general-equilibrium setup with a limited number of sectors is hardly suitable to (analytically) study the interplay between sectoral and economy-wide competitiveness and welfare. To investigate the implications of EU leadership in climate policy on gross economic welfare (abstracting from benefits of changes in environmental quality) and sectoral competitiveness, we therefore use the static multi-sector, multi-region model PACE for the world economy.

2. Policy Application: EU Leadership in Climate Policy

2.1 Analytical framework

Figure 2 lays out the diagrammatic structure of the core version of a multi-sector, multi-region computable general equilibrium model of global trade and energy (see e.g Böhringer and Vogt, 2003 – the appendix provides a detailed algebraic exposition). Primary factors of a region *r* include labour, capital, and resources of fossil fuels (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 characterise technology through substitution possibilities between various inputs.

Figure 2: 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, labour, 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 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 in a way 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 our model specification where the marginal costs of investment equals the return to investment given myopic expectations).

The model is based on recent consistent accounts of production, consumption, bilateral trade and energy flows as provided by the GTAP data base (see Badri and Walmsley, 2008, for the latest version). For the sake of compactness, the GTAP countries have been aggregated 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 composite of carbon- or energy-intensive sectors (EIS) furthermore covers most of the installations which are subject to emissions ceilings under the EU emissions trading system.

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 which produces a non-energy-intensive macro good (OTH). The primary factors in the model include labour, physical capital, and fossil-fuel resources.

Table 3 summarises the regional, sectoral, and factor aggregation of the model.

Table 3: 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	
Electricity	
Non-Energy	*Primary factors*
Energy-intensive sectors (EIS)	Labour
Rest of industry and services (OTH)	Capital
Savings good	Fixed factor resources for coal, oil and gas

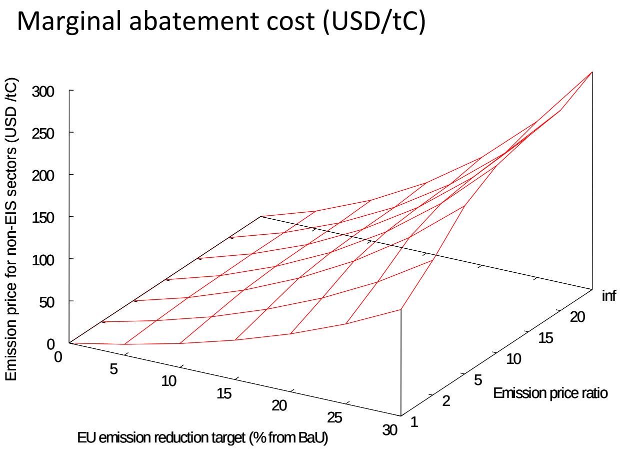
In the next section, we define the scenarios and quantify the impact of a particular policy intervention on competitiveness for different sectors in the EU together with the implications at economy-wide level.

2.2. Scenarios and Results

The EU committed itself to an ambitious unilateral climate policy which goes far beyond the commitment in the Kyoto Protocol: The Spring European Council in 2007 endorsed unilateral greenhouse gas emissions reduction of at least 20% by 2020 compared to 1990 level. Simultaneously, the concerns about the repercussions of more stringent commitments on the European competitiveness keep rising. In order to illustrate the consequences of the European Union moving forward in terms of global climate policy we assume unilateral emissions abatement within the EU while trading partners abstain from any comparable carbon emissions 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% from the reference emission level to account for a wide range of possible commitments compared to the obligations under the Kyoto Protocol (8% emissions reduction). Secondly, emissions prices for carbon-intensive EIS industries and the rest of the economy can vary: The ratio of emissions prices ranges from unity (i.e. uniform emissions pricing), via factors of 2, 5, 10, and 20 to full exemption of the carbon-intensive industries. Ratios higher than one indicate that emissions prices are discriminated in favour of carbon-intensive industries – for example a ratio of 20 implies that the carbon price in the rest of the economy is twenty times higher than for carbon-intensive industries. We use contour plots over the unilateral emissions abatement target and the emissions price ratio to visualise our results. Note that in the graphs we refer to the case of full emissions price exemptions of carbon intensive industries with a label "inf" (for the associated *infinite* price ratio). Our implementation of differential emissions pricing reflects the implications of hybrid EU climate policy where emissions-intensive installations (under the EU ETS) are facing a different scarcity price for emissions than other segments of the economy. Figures 3–6 show the implications of unilateral EU carbon policies for implied carbon taxes, economic welfare, terms of trade, sectoral production and competitiveness.

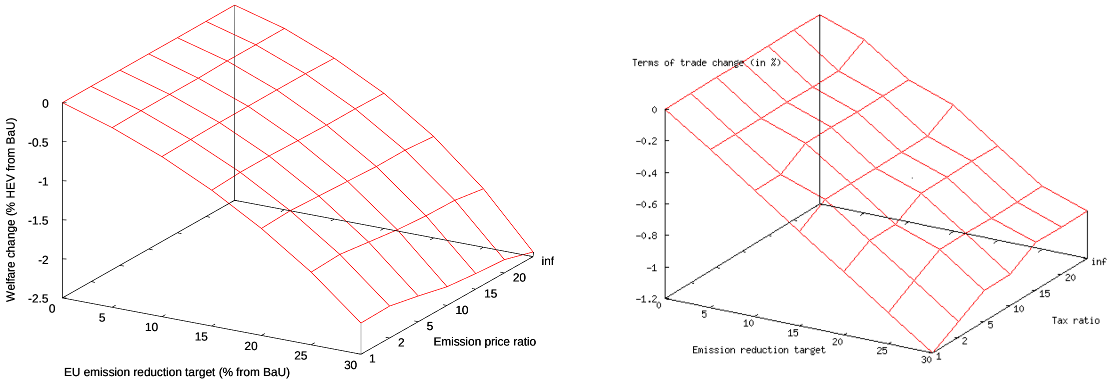
Taking the emissions price ratio as an exogenous parameter the model calculates the respective price levels for EIS and non-EIS segments achieving the exogenous EU emissions reduction target. The associated carbon values are displayed in Figure 3 which also yields – by means of the tax ratio – the lower carbon value for carbon-intensive industries. In the case of full tax exemptions to carbon-intensive industries, 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 3: Differential emissions pricing and EU-wide compliance cost



Referring to the central theme of our analysis, changes in real consumption (income) and changes in the terms of trade signal a loss in EU competitiveness at economy-wide level (Figure 4). Neglecting environmental benefits from carbon abatement, unilateral emissions constraints impose non-negligible welfare losses for the EU economy which increase when moving towards higher reduction targets and more pronounced emissions price differentiation in favour of carbon-intensive industries. For the case of the uniform emissions pricing, our core simulations indicate that welfare losses – measured as reduction in real consumption (here: the Hicksian equivalent variation) – increase from 0.76% to 2.1% for the emission reduction targets in the range between 15% and 30%. The welfare losses increase further if the EU adopts the same emissions reduction targets but fully exempts carbon-intensive industries from paying for emissions. The impact of more stringent unilateral emissions reduction targets on ToT is unambiguously negative for the uniform taxation. However, there is a qualitative difference between the two indicators regarding the implications of tax differentiation. While more pronounced tax differentiation in favour of carbon-intensive industries clearly induces additional consumption losses, the terms of trade may improve due to the possibility of tax burden shifting via higher export prices of carbon-intensive products. A change in terms of trade implies a secondary benefit for the EU and has important welfare implications for the design of the carbon abatement policies. The welfare improvements due to increasing ToT in our simulations are, however, not of such an order of magnitude to significantly reduce the domestic adjustment costs which result from foregone cheap abatement options in the carbon-intensive segments of the economy.

Figure 4: Welfare and Terms of Trade (% from Business-as-Usual)

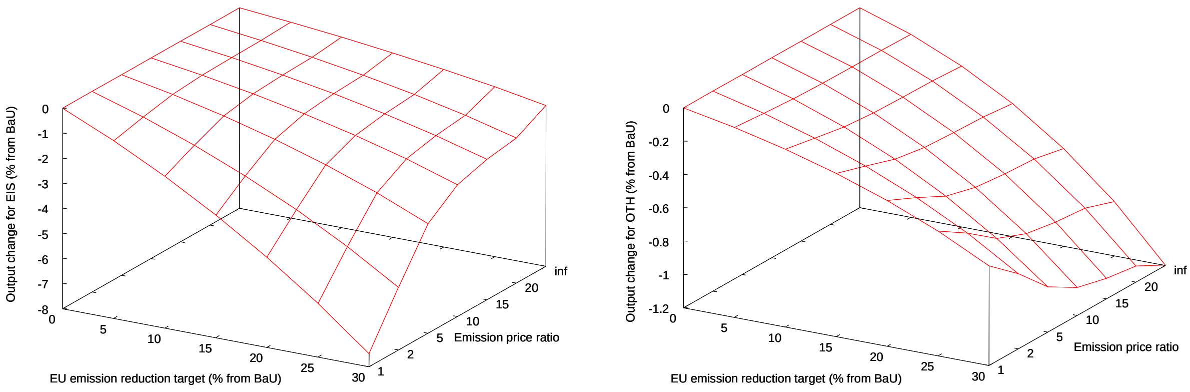


a. Welfare cost

b. Terms of trade

Figure 5 summarises the impacts of unilateral EU emissions carbon policies on sectoral production for EIS and OTH. For the case of uniform emissions pricing, the output losses for carbon-intensive industries may become quite pronounced towards higher emissions reduction targets. In turn, emissions price differentiation in favour of energy-intensive industries offsets to a large extent adverse output effects for these industries. While reduced emissions prices are clearly beneficial for carbon-intensive industries, they go at the expense of the non energy-intensive industries (OTH) which are subject to relatively higher emissions prices to meet the exogenous overall emissions reduction target. Output losses for these industries increase towards strong preferential treatment of carbon-intensive industries. However, even for an emissions reduction target of 30% and full exemption of energy-extensive industries output losses for these OTH industries are rather moderate and amount to as much as 1.2%.

Figure 5: Sectoral production (% from Business-as-Usual)



a. Energy-intensive industries (EIS)

b. Other industries and services (OTH)

The advantage of the sectoral view within a general equilibrium framework is that it enables the disaggregation of country-wide impacts on industrial competitiveness. The theoretical argument that asymmetric environmental policy could harm energy-intensive sectors and benefit non-energy-intensive sectors is well established (Jaffe et al., 1995). This outcome has been backed up in our numerical analysis – with uniform (emissions price) treatment, competitiveness in carbon-intensive sectors deteriorates, whereas non carbon-intensive sectors benefit from stringent environmental regulation according to all sectoral competitiveness indicators. But the focus here is on the magnitude in the responses of trade flows to alternative policy scenarios. Figure **6** visualises changes of the RCA, the RWS and the RTB indicators for EIS and OTH sectors, respectively, and makes the point that specific results on competitiveness effects are sensitive to the indicator used. These results are in line with literature demonstrating the weakness of revealed comparative measures when used as cardinal or ordinal measures in the non-numerical framework. With an emissions reduction target of 30% and uniform taxation, losses in sectoral competitiveness for EIS range between 3.9% (RWS) and 9.1% (the RCA) but the RTB indicator reports a loss of more than 100% compared to the BaU: The

RTB indicator responds strongly even to relatively small changes in (export and/or import) flows, while the changes of more than 100% implies the shift from 'net exporter' to 'net importer' position. Non-energy intensive sectors, however, improve sectoral competitiveness according to the RCA indicator by 1.5% (3.7%) and according to the RWS indicator by 0.8% (1.9%) with an emission reduction target of 30%, respectively; the RTB indicator shows a competitiveness improvement of more than 100%. While assessing competitiveness effects, the output measures should therefore be complemented by the competitiveness indicators as for non-energy-intensive sectors the negative output effects are consistent with the improvement of sectoral competitiveness.

An important question to policy makers is thereby to what extent the loss in sectoral competitiveness of energy-intensive sectors diminishes (abolishes) its comparative advantage (see again section 2.2). To answer this question we use the RCA index as a binary measure, an approach highly supported by previous research[11].

The existence of comparative advantage is confirmed by all three versions of indicators in the BaU for European energy-intensive sectors $RWS_{EU,ETS} > 1$, $RCA_{EU,ETS} > 1$ and $RTB_{EU,ETS} > 0$. We find a considerable consistency among indicators as a binary measure for these industries. Our results show that European energy-intensive industries are not likely to lose comparative advantage even for relatively high levels of emission reductions and all levels of tax differentiation (with few exceptions, e.g. for very stringent emissions reduction targets and uniform taxation according to the RTB indicator). The consistency in the RCA indicators as a binary measure can be partly explained by the fact that EIS have a relatively strong pronounced comparative advantage which can be diminished, but not completely destroyed by climate change policy.

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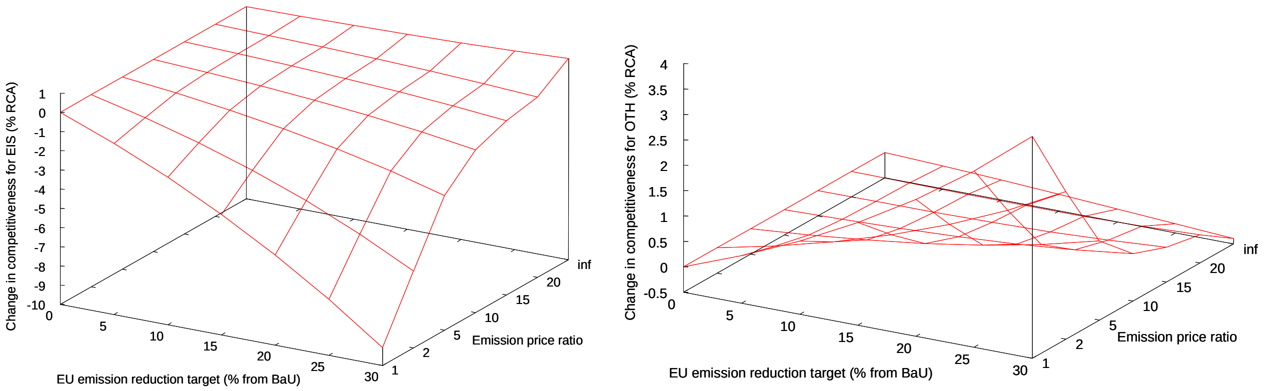
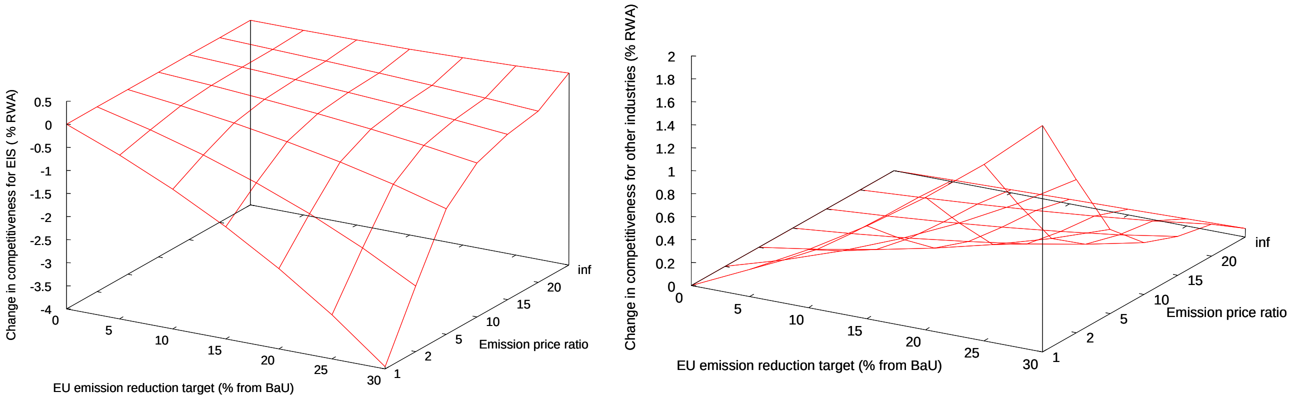
[11] Previous critical assessment of competitiveness indicators in empirical framework mainly centred on the question of their consistency when applied to the sectoral level. Finding considerable incoherence of alternative measures, Ballance et al. (1987) criticised the use of indicators such as RCA, RWS and RTB as a cardinal measure and suggested two alternative interpretations: they provide a ranking of the industries as having a higher or lower degree of comparative advantage (ordinal measure). It identifies a binary-type demarcation of industries based on comparative (dis-)advantage (dichotomous measure). The overall conclusion from this strand of literature is that indicators might be used as proxies to determine whether countries have a comparative (dis-)advantage in a particular sector, but they are less useful in indicating the extent of any comparative advantage (see Fertö and Hubbard, 2003). A much higher degree of consistency among alternative indicators used as dichotomous measures is expected to significantly reduce the sensitivity of results to a particular index chosen.

Figure 6: Competitiveness effects at sectoral level (% from Business-as-Usual)



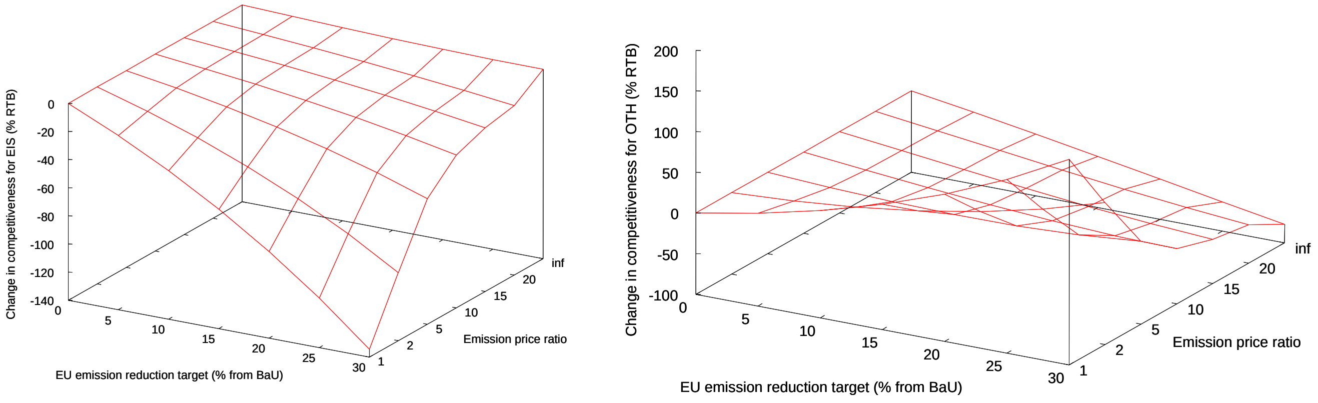
a. RCA for EIS

b. RCA for OTH



c. RWS for EIS

d. RWS for OTH



e. RTB for EIS

f. RTB for OTH

For non-energy intensive sectors, the performance of sectoral indicators as a binary measure is, however, less consistent: While RCA and RWA show a relatively small comparative disadvantage for these industries in the BaU, RTB indicates a tiny comparative advantage. Albeit non-energy intensive industries improve their competitiveness for more stringent emissions reduction targets, our simulation results show that it is very unlikely that climate change policy might turn comparative disadvantage into comparative advantage in these industries. According to the RWS indicator – a measure of performance of European energy-intensive sectors vs. direct competitors on international markets – non-energy-intensive industries maintain their comparative disadvantage for all emissions reduction targets and levels of tax differentiation.

3. Conclusions

Since the European Council started the Lisbon process in 2000, the issue of competitiveness is an area of high and rising priority within the EU. This paper demonstrates the extent and limitations to which trade-based competitiveness concepts at sectoral and national level can introduce an 'operational element' into the current discussions on EU leadership in GHG emission reduction.

One of the major methodological problems arising when dealing with competitiveness is the lack of well-defined conceptual framework. Reviewing the most recent literature on competitiveness we find much agreement on the following meta-definition: Sectoral competitiveness as a multidimensional outcome-based concept encompasses the ability of an industry to compete in international markets and to be profitable. The concept of competitiveness at national level is much less clear; even though there is a considerable support for the notion which is in line with its counterpart at sectoral level.

Employing a set of appropriate competitiveness indicators in the multi-sector, multi-region model for the world economy, we investigate the implications of alternative emissions pricing strategies under stringent unilateral carbon emissions regulation on economy-wide adjustment costs and competitiveness in the EU. From the methodological perspective, we find that the use of comparative advantage indicators within this framework can add to our understanding of changes in trade patterns in different industries, an issue that is of immense importance to the European policy makers. Results based on any (sectoral) competitiveness indicator as a cardinal measure are highly sensitive to the particular indicator chosen but we find a considerable consistency among alternative indicators as a binary measure.

Our simulations demonstrate that competitiveness effects at sectoral level depend rather on the specific policy implementation for a given emissions reduction target than on the stringency of an emissions reduction target. With uniform emissions pricing, relatively carbon-intensive industries in the EU face losses in competitiveness, while European carbon-extensive sectors improve their ability to compete internationally. In terms of conventional trade theory, ambitious climate change policy is likely to diminish but not to abolish the comparative advantage in European energy-intensive industries even if relatively stringent emissions reduction targets and a uniform tax implementation apply. This finding might provide an additional argument in the policy debate against the tax differentiation supported by conventional efficiency reasoning. Vice versa, more pronounced emissions price differentiation in favour of carbon-intensive industries can largely neutralise the negative impacts on their competitiveness and increase the economy-wide competitiveness. But it will be at the expense of competitiveness of energy-extensive sectors and overall efficiency: In our simulations, the EU is capable of improving ToT by tax differentiating in favour of energy-intensive industries and thereby shifting a part of domestic abatement costs to non-abating trade partners. Welfare-increasing implications of such ToT improvements are, nevertheless, not sufficient enough to overweigh the adverse impact of tax differentiation on welfare which results from foregone cheap abatement options in the carbon-intensive segments of the economy (loss in sectoral competitiveness in non-energy intensive sectors). This outcome makes differential emissions pricing redundant as it leads to the pending trade-off between (sector-specific) competitiveness concerns and broader economic efficiency considerations.

For a balanced view on competitiveness, it is therefore important to account for changes across the various sectors of the domestic economy rather than to focus 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. Our analysis warrants the careful and complementary use of macroeconomic and competitiveness indicators

In our assessment of EU compliance strategies, we have neglected the issue of emission leakage induced by unilateral climate policies. We therefore close with the caveat that when considering global cost efficiency differential emissions pricing strategies may be justifiable. We will leave the adequate design of leakage-compensating of sub-global climate policies to future empirical research.

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Appendix: Algebraic Model Summary

The computable general equilibrium model PACE is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers and (ii) market clearance for all goods and factors. The former class determines activity levels and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition.

In our algebraic exposition, the notation Π_{ir}^{z} is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale production of sector *i* in region *r* where *z* is the name assigned to the associated production activity. Differentiating the unit 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 *g* as an index comprising all sectors/commodities *i* (*g=i*), the final consumption composite (*g=C*), the public good composite (*g=G*), and aggregate investment (*g=I*). The index *r* (aliased with *s*) denotes regions. The index *EG* represents the subset of all energy goods (here: coal, oil, gas, electricity) and the label *FF* denotes the subset of fossil fuels (here: coal, oil, gas). 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 implemented under GAMS (Brooke et al. 1996)[12] and solved using PATH (Dirkse and Ferris 1995).[13]

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[12] Brooke, A., D. Kendrick and A. Meeraus (1996), *GAMS: A User's Guide*, Washington DC: GAMS Development Corp.

[13] Dirkse, S. and M. Ferris (1995), "The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems", *Optimization Methods & Software* 5, 123-156.

Zero Profit Conditions

1. Production of goods except fossil fuels (*g* ∉*FF*):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{E} p_{gr}^{E\,1-\sigma_{gr}^{Y}} + \left(1-\theta_{gr}^{E}\right) \left[\theta_{gr}^{M} \prod_{i \notin EG} \left(p_{igr}^{A}\right)^{\theta_{igr}^{Z}} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{K} v^{1-\sigma_{gr}^{V}} + \left(1-\theta_{gr}^{K}\right) w^{1-\sigma_{gr}^{V}} \right]^{1/(1-\sigma_{gr}^{V})} \right]^{1-\sigma_{gr}^{Y}} \right]^{1/(1-\sigma_{gr}^{Y})} \le 0$$

2. Production of fossil fuels (*g* ∈*FF*):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}^{1-\sigma_{gr}^{Q}} + (1-\theta_{gr}^{Q}) \left(\theta_{gr}^{L} w_{r} + \theta_{gr}^{K} v_{r} + \sum_{i \notin FF} \theta_{igr}^{FF} p_{igr}^{A} \right)^{1-\sigma_{gr}^{Q}} \right]^{1/(1-\sigma_{gr}^{Q})} \le 0$$

3. Sector-specific energy aggregate:

$$\Pi_{gr}^{E} = p_{gr}^{E} - \left[\sum_{i \in EG} \theta_{igr}^{E} \left(p_{igr}^{A} + p_{r}^{CO_2} a_{igr}^{CO_2} \right)^{1-\sigma_{gr}^{E}} \right]^{1/(1-\sigma_{gr}^{E})} \le 0$$

4. Armington aggregate:

$$\Pi_{igr}^{A} = p_{igr}^{A} - \left(\theta_{igr}^{A} p_{ir}^{1-\sigma_{ir}^{A}} + (1-\theta_{igr}^{A}) p_{ir}^{M\,1-\sigma_{ir}^{A}} \right)^{1/(1-\sigma_{ir}^{A})} \le 0$$

5. Aggregate imports across import regions:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left[\sum_{s} \theta_{isr}^{M} \left(p_{is} \right)^{1-\sigma_{ir}^{M}} \right]^{1/(1-\sigma_{ir}^{M})} \le 0$$

Market Clearance Conditions

6. Labor:

$$\overline{L}_{r} \ge \sum_{g} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial w_{r}}$$

7. Capital:

$$\overline{K}_{r} \ge \sum_{g} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial v_{r}}$$

8. Fossil fuel resources (g ∈*FF*):

$$\overline{Q}_{gr} \ge Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}}$$

9. Energy composite:

$$E_{gr} \ge Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}}$$

10. Import composite:

$$M_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}^{M}}$$

11. Armington aggregate:

$$A_{igr} = Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial \; p_{igr}^{A}}$$

12. Commodities (*g=i*):

$$Y_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}} + \sum_{s \neq r} M_{is} \frac{\partial \Pi_{is}^{M}}{\partial p_{ir}}$$

13. Private consumption (*g=C*):

$$Y_{Cr} p_{Cr} \geq w_r \overline{L}_r + v_r \overline{K}_r + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p_r^{CO_2} \overline{CO}_{2r} + \overline{B}_r$$

14. Public consumption (*g=G*):

$$Y_{Gr} \geq \overline{G}_r$$

15. Investment (*g=I*):

$$Y_{Ir} \geq \overline{I}_r$$

16. Carbon emissions:

$$\overline{CO}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi_{gr}^{E}}{\partial \left(p_{igr}^{A} + p_r^{CO_2} a_{igr}^{CO_2} \right)} a_{igr}^{CO_2}$$

Table A.1: Indices (sets)

G	Sectors and commodities (*g=i*), final consumption composite (*g=C*), investment composite (*g=I*), public good composite (*g=G*)
I	Sectors and commodities
r (alias *s*)	Regions
EG	Energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Fossil fuels: Coal, crude oil and gas

Table A.2: *Activity variables*

Y_{gr}	Production of item g in region *r*
E_{gr}	Energy composite for item *g* in region *r*
M_{ir}	Aggregate imports of commodity *i* and region *r*
$\mathrm{A}_{\mathrm{igr}}$	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*

Table A.3: Price variables

p_{gr}	Price of item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{E}}$	Price of energy composite for item g in region *r*
p_{ir}^{M}	Price of import composite for good *i* in region *r*
$\mathrm{p}_{\mathrm{igr}}^{\mathrm{A}}$	Price of Armington good *i* for demand category (item) *g* in region *r*
w_r	Price of labour (wage rate) in region *r*
v_r	Price of capital services (rental rate) in region *r*
q_{ir}	Rent to fossil fuel resources in region *r* (*i* ∈ FF)
$\mathrm{p}_{\mathrm{r}}^{\mathrm{CO_2}}$	Carbon value in region *r*

Table A.4: Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labour endowment for region *r*
$\overline{K}_r$	Aggregate capital endowment for region *r*
$\overline{Q}_{ir}$	Endowment of fossil fuel resource *i* for region *r* ($i \in$ FF)
$\overline{B}_r$	Initial balance of payment deficit or surplus in region *r* (note: $\sum_r \overline{B}_r = 0$)
$\overline{\mathrm{CO}}_{2\mathrm{r}}$	Endowment of carbon emission rights in region *r*
$\mathrm{a}_{\mathrm{igr}}^{\mathrm{CO}_2}$	Carbon emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)

Table A.5: Cost shares

$\theta_{\mathrm{gr}}^{\mathrm{E}}$	Cost share of energy in the production of item *g* in region *r*
$\theta_{\mathrm{gr}}^{\mathrm{M}}$	Cost share of the non-energy (material) aggregate within the composite of value-added and material in the production of item *g* in region *r*
$\theta_{\mathrm{gr}}^{\mathrm{K}}$	Cost share of capital within the value-added of item *g* in region *r*
$\theta_{\mathrm{igr}}^{\mathrm{Z}}$	Cost share of good *i* in the non-energy (material) aggregate of item *g* in region *r*
$\theta_{\mathrm{gr}}^{\mathrm{Q}}$	Cost share of fossil fuel resource in fossil fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{gr}}^{\mathrm{L}}$	Cost share of labour in non-resource inputs to fossil fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{gr}}^{\mathrm{K}}$	Cost share of capital in non-resource inputs to fossil fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{igr}}^{\mathrm{FF}}$	Cost share of good *i* in non-resource inputs to fossil fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{igr}}^{\mathrm{E}}$	Cost share of energy good *i* ($i \in EG$) within the energy composite of item *g* in region *r*
$\theta_{\mathrm{igr}}^{\mathrm{A}}$	Cost share of domestic output *i* within the Armington good (demand category) *g* of region *r*
θ_{isr}^{M}	Cost share of exports of good *i* from region *s* within the import composite of good *i* in region *r*

Table A.6: Elasticities

σ_{gr}^{Y}	Substitution between the energy composite and the material-value-added aggregate in the production of item *g* in region *r*
σ_{gr}^{V}	Substitution between capital and labour within the value-added nest of production of item *g* in region *r*
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in fossil fuel production (*g* $\in$ FF) of region *r* (calibrated consistently to exogenous supply elasticities)
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in the production of item *g* in region r
	Substitution between coal and the liquid fossil fuel composite in production
σ_{ir}^{A}	Substitution between the import composite and the domestic input to Armington production of good *i* in region *r*
σ_{ir}^{M}	Substitution between imports from different regions within the import composite for good *i* in region *r*

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

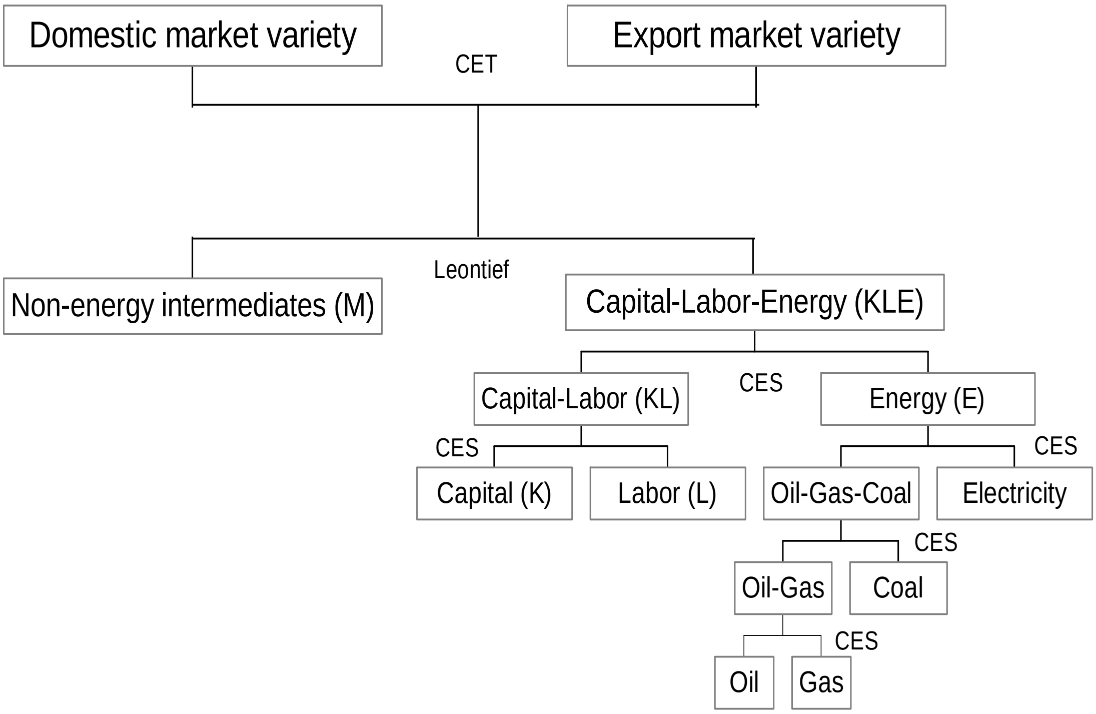

Figure A.2: Nesting in fossil fuel production

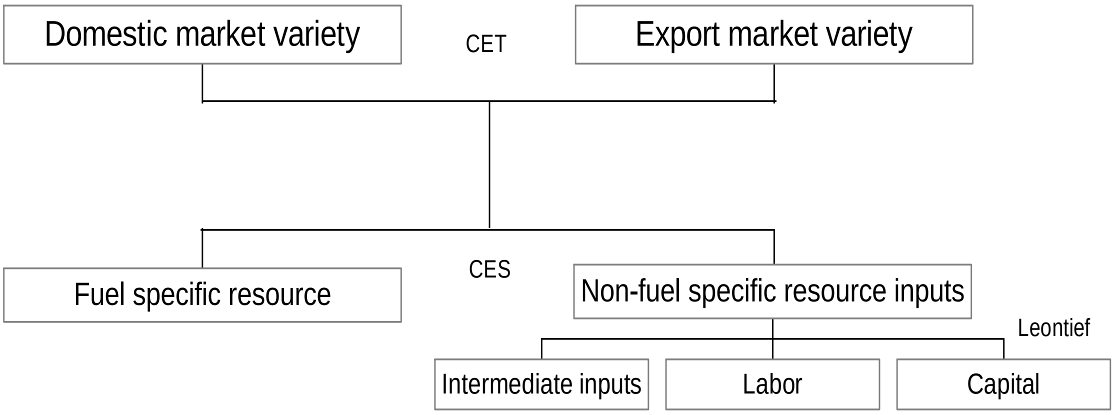

Figure A.3: Nesting in household consumption

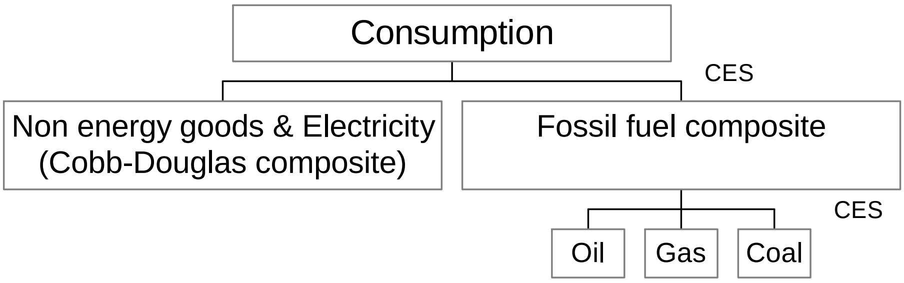

Figure A.4: Nesting in Armington production