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EU Climate Policy Up to 2020: An Economic Impact Assessment

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Abstract. In its fight against climate change the EU is committed to reducing its overall greenhouse gas emissions to at least 20% below 1990 levels by 2020. To meet this commitment, the EU builds on segmented market regulation with an EU-wide cap-and-trade system for emissions from energy-intensive installations (ETS sectors) and additional measures by each EU Member State covering emission sources outside the cap-and-trade system (the non-ETS sector). Furthermore, the EU has launched additional policy measures such as renewable energy subsidies in order to promote compliance with the climate policy target. Basic economic reasoning suggests that emission market segmentation and overlapping regulation can create substantial excess costs if we focus only on the climate policy target. In this paper, we evaluate the economic impacts of EU climate policy based on numerical simulations with a computable general equilibrium model of international trade and energy use. Our results highlight the importance of initial market distortions and imperfections as well as alternative baseline projections for the appropriate assessment of EU compliance cost.
Keywords: climate policy, market distortions; baseline projections, computable general equilibrium

JEL classification: D58, Q48, Q54

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1. Introduction

The European Union (EU) considers itself as a forerunner in climate protection and the market-based implementation of climate policy. Indeed, the EU is so far the only geopolitical region that has adopted a binding unilateral greenhouse gas emission reduction target for 2020.[1] Likewise, the EU has elaborated a detailed emission reduction strategy which pursues market-based regulation in order to minimize economic adjustment costs. The consistency of the EU market-based climate policy regulation however has been repeatedly put into question for two major reasons. Firstly, under the current EU legislation the EU partitions its emission market into (at least) two segments. Secondly, the EU uses a broader policy mix instead of one single instrument to meet its climate policy target. In this paper, we investigate the potential for excess costs due to emission market segmentation and overlapping regulation.

[1] At the Spring Summit in March 2007, the European Council has agreed upon an ambitious climate policy with unilateral greenhouse gas emissions reductions in 2020 by at least 20% compared to 1990 levels. This target was put into legal force in December 2008 upon mutual agreement between the European Council, the European Parliament, and the European Commission.

Economic textbook analysis provides clear-cut guidelines for how to impose an emission cap at minimum costs: The marginal cost (price) to each use of a given pollutant should be equalized thereby assuring that the economy as a whole employs the cheapest abatement options. The cost-effective solution can be decentralized through the implementation of a comprehensive emissions trading scheme which covers all emission sources and establishes one uniform emission price. The beauty of such a cap-and-trade system is that no central planner information on specific abatement possibilities is required in order to achieve the cost-effective outcome; the market will work it out – which is the quintessence of market-based regulation. A second simple textbook insight based on the seminal work of Tinbergen (1952) is that in order to reach one policy target only one policy instrument should be used.[2] A mix of policy instruments in order to pursue a single policy objective "will be at best redundant and at worst counterproductive" (Johnstone, 2003). To sum up: Both, segmentation of emission markets with differential emission pricing as well as the use of multiple climate policy instruments produce excess cost, i.e. make climate policy more expensive than necessary.

How does the actual implementation of EU climate policy comply with these basic economic principles? The EU has launched an EU-internal emission trading scheme (EU ETS) as the central pillar to achieve its greenhouse gas emission reduction target (for a review see e.g. Ellerman and Joskow, 2008). However, the EU ETS only includes energy-intensive installations covering less than 50 % of EU-wide greenhouse gas emissions. In order to meet the overall EU emission reduction target, each EU Member State has been assigned complementary emission reduction targets for the non-ETS sectors (e.g. buildings, transport, and agriculture) which must be achieved with additional domestic policy measures. In principle, governments can trade emissions for the non-ETS sectors such that a uniform pricing of non-ETS abatement within the EU seems at least in principle feasible (see Tol, 2009 for a discussion of alternative flexibility rules for non-ETS sectors). The mandated 20 % EU-wide emission reduction by 2020 as compared to 1990 is split down into a 21 % emission reduction requirement for the ETS sector and a 10 % emission reduction requirement for the non-ETS sector taking 2005 as the reference year. Due to the missing linkage of non-ETS and ETS sectors, however, the actual EU climate policy regime segments the EU-wide emission market, thereby creating the potential for substantial excess costs (see e.g. Böhringer, 2005). Another source of excess costs can be traced back to the use of multiple policy instruments for achieving the emission reduction target. Beyond emissions trading the EU builds upon the explicit promotion of renewable energy production and energy efficiency both in ETS as well as non-ETS segments of the economy. From the sole perspective of EU greenhouse gas emission reduction, such a policy instrument mix bears the risk of costly overlapping regulation. In a broader perspective, the policy mix may be justified by multiple targets as stated in the EU "20-20-20" Climate Action and Renewable Energy Package through which the EU pursues a 20 % share of renewable energy sources in gross final energy consumption and an

[2] While more targets than instruments makes targets incompatible, more instruments than targets makes instruments alternative (i.e. one instrument may be used instead of another or a combination of others).

increase of energy efficiency of 20 % by 2020 along with its greenhouse gas emission reduction target (EU, 2008a). However, while global warming provides a straightforward argument for the policy objective of curbing greenhouse gas emissions, the objectives behind renewable energy quotas and energy efficiency targets are less obvious. In the policy debate, reasons such as energy security or strategic technological innovation are emphasized in addition to climate protection. Yet again, if emission reduction is the central policy objective, multiple instruments are likely to create excess costs. Alternatively, we may refer to the additional costs as a price tag that must be attached to the value of other objectives such as decreased reliance on fossil fuels or improved technological progress.

There is an important caveat against the strict adherence to simple textbook principles when we deal with applied policy analysis. Uniform pricing of greenhouse gas emissions as well as the adoption of the simple Tinbergen rule will in general no longer hold as rigorous conditions for cost-effectiveness if we account for second-best regimes reflecting initial tax distortions, market power, external knowledge spillovers, transaction costs, uncertainty, etc. Theoretical second-best analysis can deliver useful qualitative insights but it lacks actual policy relevance because of very restrictive assumptions in order to preserve analytical tractability.

Against this background, we use numerical analysis based on empirical data to investigate the potential excess costs of EU market segmentation and overlapping regulation through renewable quotas. For reasons of policy relevance and tractability, we refer to uniform emission pricing as our benchmark for comparison rather than a hypothetical cost-effective mixture of differentiated emission prices and renewable targets. In our numerical simulations, we make use of PACE, a large-scale multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use where we implement the actual segmentation of the EU emission market and the imposition of renewable quotas. We identify substantial excess costs of market segmentation with differential emission pricing for ETS and non-ETS sectors as compared to uniform emission pricing. The additional costs of renewable targets on top of an emission quota are modest; this is mainly due to the fact that emission regulation "stand-alone" already leads to a substantial increase in green power production such that additional subsidies to meet the targeted renewable shares are relatively small.[3] Our quantitative results (driven by the assumptions on economic interactions and the data used for parameterization of our CGE model) illustrate in particular the potential pitfalls of emission market segmentation between ETS and non-ETS sectors: Whenever the central planner falls short of sufficient information on the emission abatement possibilities along the time path there is the risk of a larger spread in marginal abatement costs across polluters which in turn may substantially increase the direct emission abatement costs as well as economy-wide compliance cost.[4] In the presence of market

[3] In addition, we treat EU-27 as a single region in our numerical analysis which is likely to underestimate the EU-wide costs of renewables promotion since EU Member States have adopted differentiated measures rather than implemented a tradable green quota.

[4] If there are no substantial initial distortions that can be – consciously or by incidence – ameliorated with differential emission pricing or/and overlapping regulation.

distortions such as initial taxes or international market power, however, departure from uniform emission pricing can be welfare-improving as long as the increase in direct abatement costs due to differential emissions pricing is more than offset through the amelioration of initial tax distortions or potential terms-of-trade gains. Beyond the complex implications of initial tax distortions and international market power, the baseline sensitivity analysis recalls the need for robustness checks of policy messages with respect to underlying data. Given larger uncertainties in baseline projections – inherent to the current global economic turmoil – policy advisers as well as policy makers should not pretend certainty on macroeconomic impacts with single-point estimates but rather discuss the reasoning behind some sensible cost intervals.[5]

Our paper is organized as follows: Section 2 illustrates the basic efficiency argument for uniform emission pricing. Section 3 presents a non-technical overview of the PACE model underlying our quantitative assessment.[6] Section 4 lays out our core policy scenarios and summarizes simulation results. Section 5 discusses sensitivity analysis for alternative baseline projections. Section 6 concludes.

2. Cost-effectiveness of Emission Abatement: Stylized Analysis and Caveats

The efficiency rationale for uniform pricing of emissions is straightforward when we focus on competitive emission markets and abstract from initial market distortions. In formal terms, cost-effectiveness of emission reduction policies comes down to minimizing the sum of abatement costs across all sectors i of the economy, i.e., $\underset{a_i}{Min} \sum_i C_i(a_i) \;\; s.t. \; \sum_i a_i = \overline{A}$ where $C_i(a_i)$ denotes the abatement cost function[7] in sector i for emission abatement a_i and $\overline{A}$ is the abatement requirement which equals the difference between baseline emissions E^0 and the exogenous cap $\overline{E}$. The associated first-order condition states that marginal abatement costs $C_i^{'} = \partial C_i / \partial a_i = \tau$ are equalized across all sectors where the Lagrangian multiplier τ indicates the uniform price (opportunity cost) for one unit of emissions. Market-based regulation through an emissions trading system which covers all sectors of the economy will warrant the cost-effectiveness through an economy-wide uniform emission price τ. As laid out in section 1, the actual EU climate policy regime generates (at best) two segmented emission markets – one for ETS sectors and another one for non-ETS sectors (assuming perfect flexibility across non-ETS sectors of all Member States). As long as these two markets are not linked, decentralized emissions trading can not lead to a uniform emission price but the latter must be established through an appropriate exogenous split of the overall emission cap on behalf of an omniscient central planner.

[5] Apparently, the same argument applies with respect to the ambiguities of model assumptions.
[6] See Böhringer et al. (2009a) for a detailed description of the generic model.
[7] As usual, $\partial C_i / \partial a_i \geq 0$ and $\partial^2 C_i / \partial a_i^2 \geq 0$.

We can graphically illuminate the potential pitfall of EU emission market segmentation based on marginal abatement cost curves for the year 2020 which have been calculated in the PACE model.

Figure 1 sketches the marginal abatement cost curves for the ETS and the non-ETS sectors. Together these curves add up to the aggregate marginal abatement cost curve (labeled "Total"). Total abatement $\overline{A}$ in 2020 equals the difference between baseline emissions E^0 and the exogenous emission ceiling $\overline{E}$ imposed by the EU where the baseline emissions E^0 are taken from the IEO reference baseline.

Comprehensive emissions trading leads to a uniform EU-wide emission price τ at the intersection of the vertical (inelastic) abatement demand function $\overline{A}$ and the aggregate marginal abatement cost curve. The efficient allocation of abatement burden between ETS and non-ETS sectors, i.e. A^*_{ETS} and $\mathrm{A}^*_{\mathrm{non-ETS}}$, will be endogenously determined through the uniform emission price τ .

Figure 2 recasts the efficient partitioning of total abatement across the ETS and non-ETS sectors within a box diagram where the width corresponds to the total abatement requirement $\overline{A}$ in 2020. Following Coase (1960), the initial allocation of abatement requirements will not matter for the efficient outcome as long as there is emission trading between ETS and non-ETS. However, if markets are segmented, the initial allocation of abatement burden must exactly equal the efficient split in order to assure overall cost-effectiveness. In Figure 2 emissions ceilings for ETS and non-ETS sectors must then be chosen such that $E^0_{ETS} - \overline{E}_{ETS} = \overline{A}_{ETS} = A^*_{ETS}$ and $\mathrm{E}^0_{\mathrm{non-ETS}} - \overline{\mathrm{E}}_{\mathrm{non-ETS}} = \overline{\mathrm{A}}_{\mathrm{non-ETS}} = \mathrm{A}^*_{\mathrm{non-ETS}}$. To do so, the EU planning authority would require perfect information on the future effective abatement requirement as well as the future marginal abatement cost curves for ETS and non-ETS sectors. Figure 2 indicates that the exogenous EU partitioning of the overall emission budget $\overline{E}$ between ETS and non-ETS sectors (i.e. the implicit abatement requirements $\overline{A}^{EU}_{ETS}$ and $\overline{\mathrm{A}}^{\mathrm{EU}}_{\mathrm{non-ETS}}$) is rather inefficient from a simplified partial equilibrium perspective if we adopt the IEO reference baseline and the PACE model. The excess costs associated with differential emission pricing are sketched by the shaded area.[8] In contrast, the EU Impact Assessment (EU, 2008b) considers the actual EU partitioning between ETS and non-ETS sectors to be cost-effective based on the baseline assumptions and model mechanisms implicit to the PRIMES energy system model for the EU (see e.g. Antoniou and Capros, 1999). According to the PRIMES calculation an efficient split between ETS and non-ETS sectors comes down to emission reduction requirements of 21 % (ETS) and 10 % (non-ETS) vis-à-vis the sector-specific emission levels in 2005. According to the PACE calculations with the business-as-usual projections as of IEO, the emission reduction requirement for ETS should be rather around 30 % whereas the Non-ETS sector would be allocated roughly its 2005 emissions.

[8] In our graphical exposition as well as in the subsequent numerical simulations of section 4, we assume uniform pricing of emissions within the non-ETS sectors which we treat as a single EU-wide aggregate.

Figure 1: ETS and non-ETS marginal abatement cost curves for EU-27 in 2020

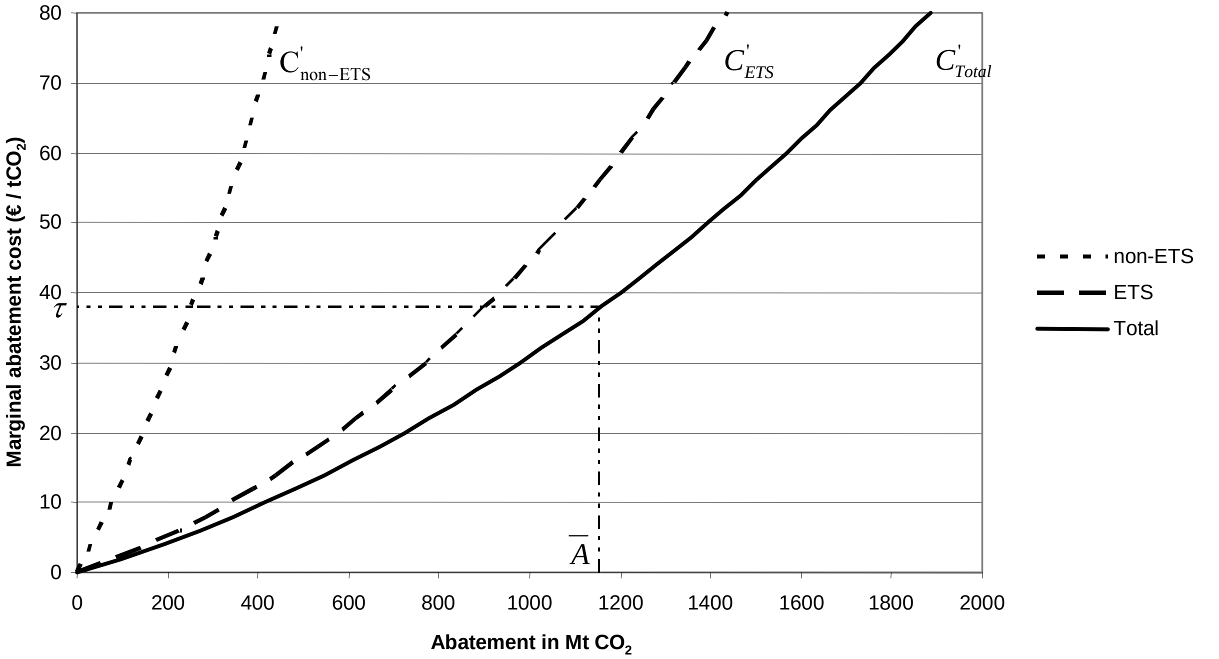
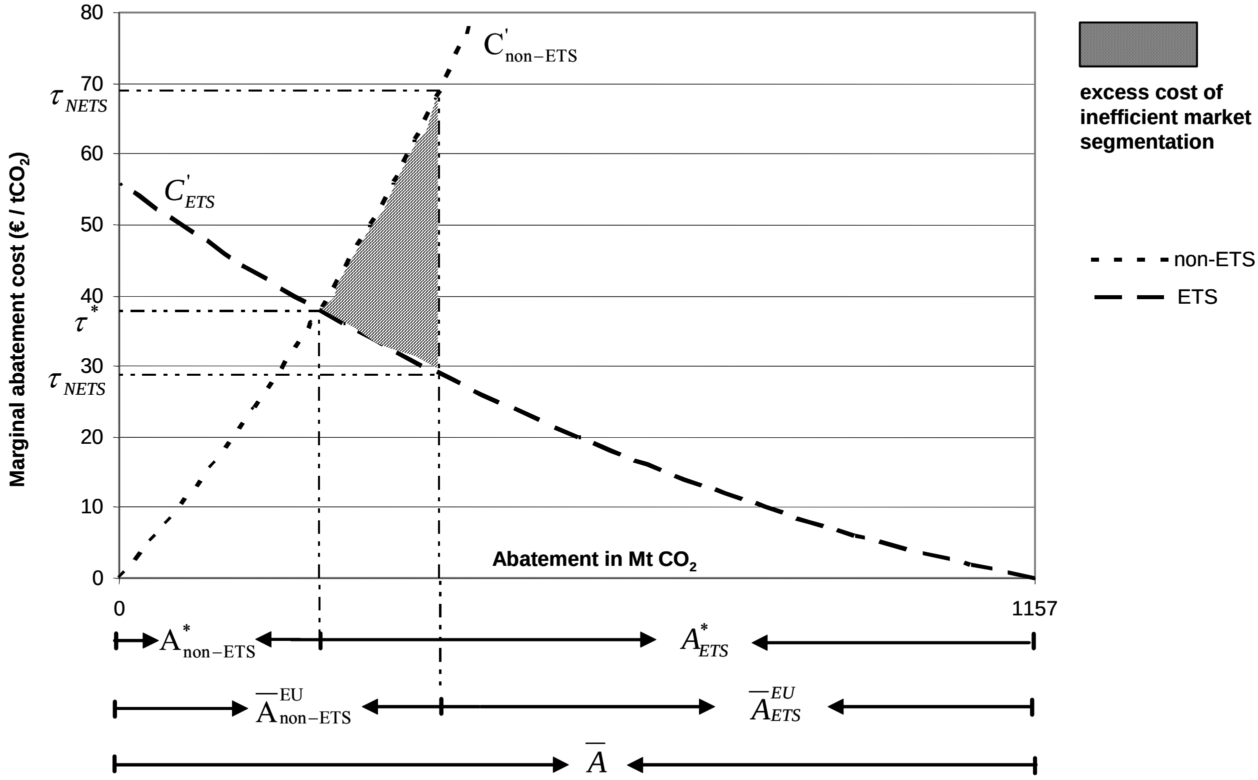


Figure 2: Excess costs of emission market segmentation



It should be stressed that our stylized partial equilibrium analysis hinges on the assumption that private and social marginal abatement costs coincide. In this case, uniform emission pricing will provide a cost-effective solution. However, as already mentioned, private and social marginal abatement costs typically diverge in policy practice: If we take into account real-world market imperfections and distortions, uniform emission pricing will no longer be socially optimal. For example, international spillover effects may provide efficiency arguments to deviate from uniform taxation of greenhouse gas emissions if a unilaterally acting region such as the EU is able to exploit terms of trade or aims at leakage adjustment to increase global environmental effectiveness (see e.g. Böhringer et al., 2009a). Initial distortionary taxes are another important reason why uniform pricing of emissions may no longer be optimal as private and social marginal abatement costs diverge. Likewise, the use of multiple instruments may be beneficial if they alleviate pre-existing distortions.[9] For pragmatic reasons, uniform emission pricing may nevertheless serve as a meaningful benchmark for the calculation of potential excess costs induced by market segmentation and overlapping regulation.

3. Model Structure and Model Calibration

3.1. Model Structure

In order to quantify the cost implications of alternative strategies for EU climate policy compliance we use PACE, an established multi-region, multi-sector computable general equilibrium (CGE) model of global trade and energy use. A multi-region setting is indispensable for the economic impact analysis of climate policy regimes: In a world that is increasingly integrated through trade, policy interference in larger open economies not only causes adjustment of domestic production and consumption patterns but also influences international prices via changes in exports and imports. The changes in international prices, i.e., the terms of trade, imply secondary effects which can significantly alter the impacts of the primary domestic policy. In addition to the consistent representation of trade links, a detailed tracking of energy flows is a pre-requisite for the assessment of climate policies. Combustion of fossil fuels is a driving force of global warming through the release of the main greenhouse gas CO_2.

Figure 3 provides a diagrammatic structure of the multi-sector, multi-region CGE model in use for our numerical analysis. A representative agent RA_r in each region r is endowed with three primary factors: labor $\overline{L}_r$, capital $\overline{K}_r$, and fossil-fuel resources $\overline{Q}_{ff,r}$ (used for fossil fuel production). Labor and capital are intersectorally mobile within regions but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region.

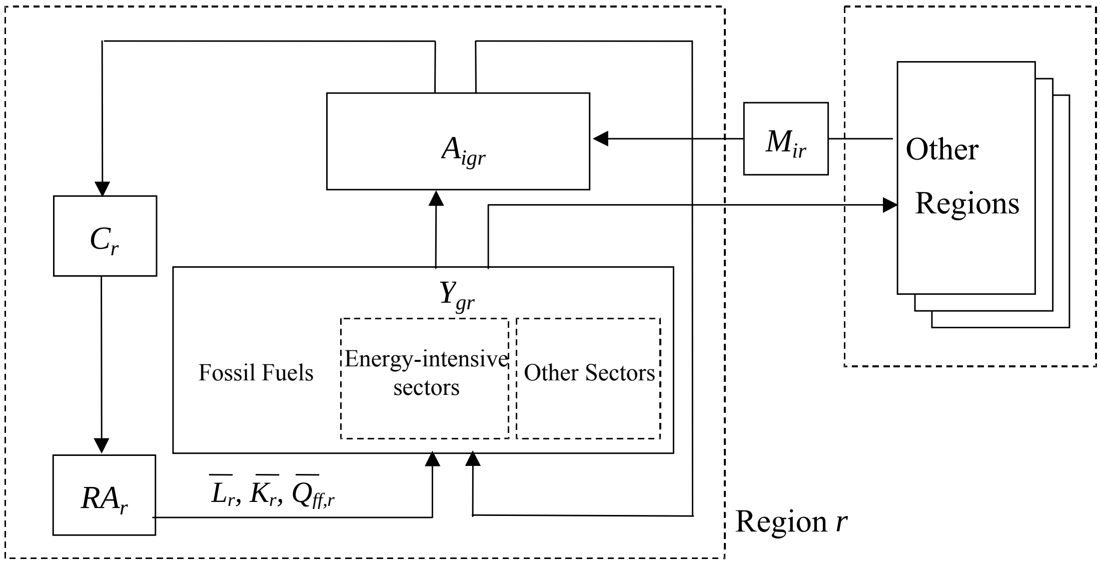
Production Y_{gr} of commodity g, other than primary fossil fuels and electricity production, is captured by three-level constant elasticity of substitution (CES) cost functions that describe the price-dependent use of capital, labor, energy, and material in production.[10] At the top level, a CES material composite trades off with an aggregate of energy, capital, and labor subject to a constant elasticity of substitution.

[9] Of course, deviation form first-best principles in a second-best world may also worsen rather than ameliorate initial distortions.

[10] The index g comprises production outputs by sectors (indexed i) as well as the final consumption composite, the investment aggregate and the public good aggregate.

At the second level, a CES function describes the substitution possibilities between the energy aggregate and a value-added composite. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function and different energy inputs enter the energy composite subject to a constant elasticity of substitution. Power production is captured by a set of discrete power generation technologies delivering a homogeneous electricity good. Each technology is represented by a two-level nested CES with a fixed factor at the top level which can be calibrated to a given elasticity of supply. Likewise, in the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with empirical estimates for the price elasticity of fossil fuel supply.

Figure 3: Diagrammatic overview of the model structure



Final consumption demand C_r in each region is determined by the representative agent who maximizes utility subject to a budget constraint with fixed investment (i.e. given demand for the savings good) and exogenous government provision. Total income of the representative household consists of factor income and taxes. Consumption demand of the representative agent is given as a CES composite that combines consumption of energy and a non-energy goods aggregate. Substitution patterns within the non-energy consumption bundle are reflected via a CES function; the energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution.

Bilateral trade is specified following the Armington approach of product heterogeneity (Armington, 1969), i.e., domestic and foreign goods are distinguished by origin. All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{igr} that combines the domestically produced good Y_{ir} and the imported good M_{ir} from other regions differentiated by demand category g (i.e., the composition of the Armington good differs across sectors, final consumption demand, investment demand, and public good demand). Domestic production Y_{ir} either enters the formation of the Armington good A_{igr} or is exported to satisfy the import demand of other regions. The balance of payment constraint, which is warranted through flexible exchange rates, incorporates the benchmark trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels with CO_2 coefficients differentiated by the specific carbon content of fuels. CO_2 emission abatement can take place by fuel switching (inter-fuel substitution) or energy savings (either by fuel-non-fuel substitution or a scale reduction of production and final demand activities). Revenues coming from the imposition of the CO_2 emission constraint are recycled lump-sum to the representative agent in the respective region. CO_2 emission abatement policies are introduced via an additional constraint that holds CO_2 emissions to a specified limit.

For the impact assessment of EU climate policies the model is implemented as a sequence of static equilibria with investment and government demands exogenously scaled at the exogenous baseline growth rates (see section 5.2. for details on the forward calibration).

3.2. Model Calibration

The model builds on the most recent GTAP dataset with detailed accounts of regional production, regional consumption, bilateral trade flows as well as energy flows and CO_2 emissions for the year 2004 (Badri and Walmsley, 2008). The dataset also features a variety of initial taxes. As is customary in applied general equilibrium analysis, base year data together with exogenous elasticities determine the free parameters of the functional forms (Mansur and Whalley, 1984). Elasticities in international trade are based on empirical estimates reported in the GTAP database. Substitution elasticities between production factors (capital, labor, energy inputs, non-energy inputs) are taken from Okagawa and Ban (2008) who provide empirical estimates based on panel data across sectors and industries for the period 1995 to 2004.

As to sectoral and regional model resolution, the GTAP database is aggregated towards a composite dataset that accounts for the specific requirements of international climate policy analysis. At the sectoral level the model captures details on sector-specific differences in factor intensities, degrees of factor substitutability and price elasticities of output demand in order to trace back the structural change in production induced by policy interference. The energy goods identified in the model are coal, crude oil, natural gas, refined oil products, and electricity. This dis-aggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. The model then features important CO_2-(energy-)intensive industries which are potentially most affected by carbon abatement policies: Mining, chemical industry, air transport, other transport, non-metallic minerals, iron and steel industry, non-ferrous metals, paper-pulp-print.[11] The remaining sectors include transport equipment, other machinery, food products, wood and wood-products, construction, textiles-wearing apparel-leather, other manufacturing, agricultural products, commercial and public services, as well as dwellings. As to regional disaggregation, the model covers the EU-27 and all other Annex B regions that either face binding emission reduction commitments under the Kyoto Protocol (Australia and New Zealand, Canada, Japan, and Russia) or are expected to adopt some emission ceilings in the run-up to 2020 (USA). Furthermore, we include explicitly central developing regions that are at the same time important trading partners of the EU and larger greenhouse gas emitters (China, India, Brazil, Mexico, and the composite region of South Korea, Indonesia and Malaysia). All other countries are summarized within an aggregate Rest of the World.

The costs of complying with future emission constraints are directly linked to the structural characteristics of each particular economy exhibited in a hypothetical business-as-usual situation without such emission constraints. In our comparative-static analysis we use official projections of the International Energy Outlook (EIA, 2008)) to infer the business-as-usual structure of the model's regions – i.e. the reference situation without exogenous emissions constraints – for 2020 which is the target year of the EU climate policy regulation. A simple forward projection of the model from the 2004 base year to the 2020 target year would involve calibration to a steady-state where all physical quantities (including CO_2 emissions) grow at an exogenous uniform rate while relative prices remain unchanged. The virtue of a steady-state baseline is that it provides a transparent reference path for the evaluation of policy interference. Any structural change in the counterfactual can be attributed to the new policy. Such a steady-state forward calibration, however, lacks policy appeal. Policy makers are typically confronted with off-the-steady-state projections for non-uniform growth rates and heterogeneous structural dynamics. Off-the-steady-state exogenous baseline projections pose considerable challenges to CGE-based policy analysis as the latter stands out for a high degree of endogeneity in economic variables. Owing to the critical importance of baseline projections for the economic impact assessment of future climate policy constraints, section 5.2. lays out in detail our forward-calibration technique to exogenous projections in economy growth and energy demands.

4. Policy Scenarios and Simulation Results

4.1. Policy Scenarios

In our numerical analysis we want to investigate the potential excess costs of EU climate policy due to emission market segmentation and promotion of renewable energy production as compared to a comprehensive EU cap-and-trade system. The EU renewable policy target is formulated with respect to gross final energy consumption. Since our model only tracks renewable energy within the electricity sector, we assume the renewable target of 20 % in gross final energy consumption to be roughly

[11] In our model the EU-ETS covers the following sectors: electricity, refined oil products, non-metallic mineral products, iron and steel industry, non-ferrous metals, and paper-pulp-print.

equivalent to a 30 % renewable energy share in electricity production. The latter then is referenced in our simulations as renewable portfolio standard (RPS).

In total, we define four core scenarios that combine alternative assumptions on the pricing of CO_2 emissions from different segments of the economy (uniform pricing versus differential ETS/non-ETS pricing) and the imposition of renewable portfolio standards (no RPS versus RPS regulation):[12]

- *uniform*: This scenario achieves the EU-wide emission reduction target through a comprehensive cap-and-trade system that includes all EU emission sources and implies a uniform CO_2 price. It serves as the benchmark for comparison with those scenarios that feature emission-market segmentation and/or the imposition of renewable targets.
- *ets*: This scenario reflects the hybrid carbon emission regulation as imposed by the EU Climate Action and Renewable Energy Package (EU, 2008a) where emissions from energy-intensive industries (ETS sectors) are limited through an EU-wide cap-and-trade system and the remaining sectors outside the trading system (non-ETS sectors) require complementary regulation in each Member State. The aggregate emission ceiling in 2020 for the EU can be related to 2005 historic emission levels for ETS and non-ETS sectors with cutback requirements of 21 % below 2005 emission levels for ETS sectors and of 10 % below 2005 emission levels for the non-ETS sectors respectively.
- *uniform+rps*: This scenario includes the 30 % green quota in EU electricity generation on top of a comprehensive EU emissions trading system as captured by scenario *uniform*.
- *ets+rps*: This scenario includes the 30 % green quota in EU electricity generation on top of the hybrid carbon emission regulation as captured by scenario *ets*.

In our model simulations with 5-year time intervals we assume a linear implementation path of emission reduction targets and the RPS up to 2020 taking 2005 as the starting year. We quantify the economic adjustment cost across the four central case scenarios with respect to a business-as-usual scenario associated with baseline projections for economic development and emission growth. Our reference baseline projections (*ref*) are taken from the International Energy Outlook (IEO) by the U.S. Energy Information Agency (EIA, 2008). The IEO projections stand out for their global coverage including various geopolitically important regions such that we are able to incorporate region-specific developments beyond EU-27 in the forward calibration of our model.

4.2. Simulation Results

Figures 4 and 5 illustrate the pitfalls of the actual EU climate policy design with respect to emission market segmentation and overlapping regulation. As displayed in Figure 4, the hybrid EU emission

[12] The core scenarios for EU climate policy are identical with the EU transitional climate policy scenarios provided by EMF 22 (see Böhringer et al. 2009b). For all non-EU regions we adopt the default assumptions on domestic climate policy action as specified by EMF 22. Apart from country-specific reduction targets the default EMF prescriptions do not foresee any international emission trading (outside EU-27). Note that emission reductions in our policy simulations refer to CO_2 emissions only.

regulation – incorporated in scenarios *ets* and *ets+rps* – leads to a drastic difference between marginal abatement cost in ETS and non-ETS sectors. The huge price differentials indicate scope for substantial cost savings if the EU emissions trading system were (more) comprehensive.

Figure 4: Marginal abatement (€ per metric ton of CO_2)

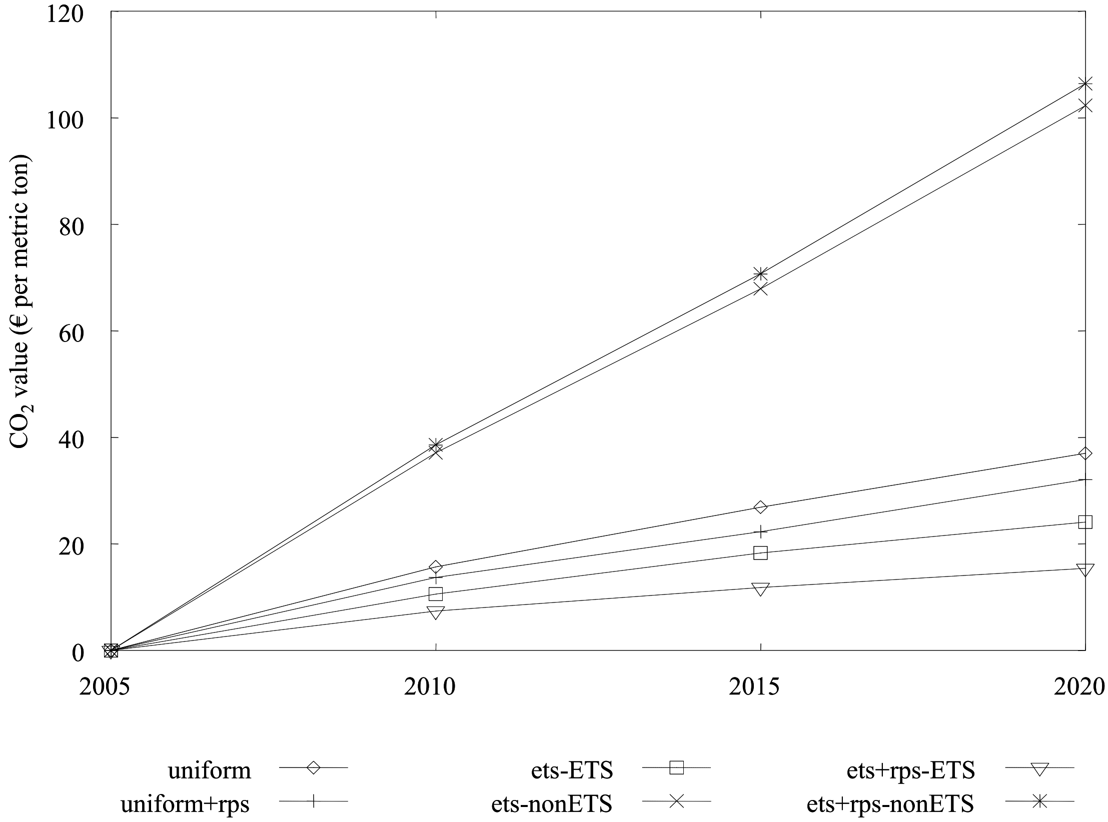


Figure 5: Compliance costs (% Hicksian equivalent variation in income – HEV)

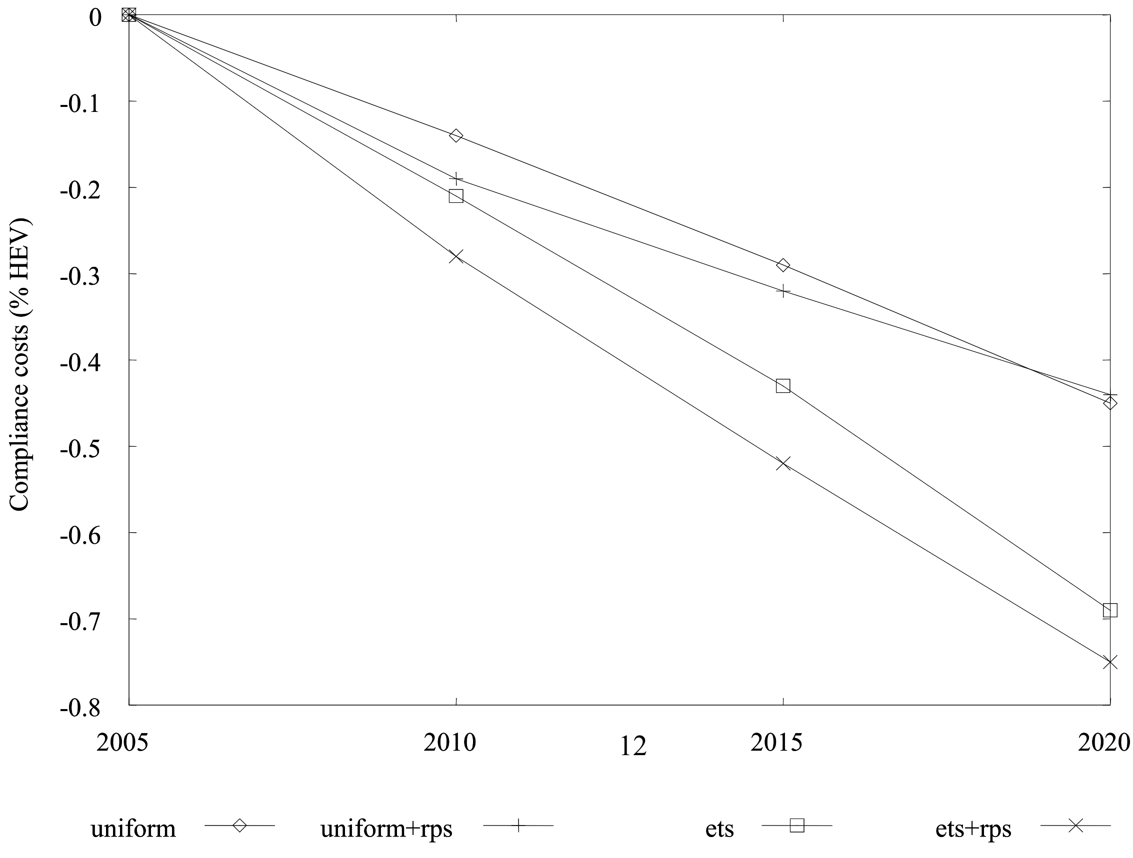


Figure 4 furthermore depicts the downward pressure of green quotas on emission prices: An increased share of emission-free renewables that is induced through binding RPS reduces the shadow price on emission constraints – the CO_2 prices thus decreases. Figure 5 reveals sizeable excess costs due to emission market segmentation. In addition, the issue of counterproductive overlapping regulation arises if the main objective of regulation is to reduce emissions of CO_2. In relative terms, the excess costs of hybrid emission regulation are much more pronounced in our model and scenario parameterization than the additional cost of RPS. The rather small excess costs of RPS is due to the fact that emission regulation stand-alone already leads to a substantial increase in green power production such that additional subsidies to meet the targeted RPS are rather small.[13] Economic costs in Figure 5 are reported as Hicksian equivalent variation (HEV) in income which denotes the amount which is necessary to add to (or deduct from) the benchmark income of the representative consumer so that she enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices.

For an appropriate interpretation of our core simulation results it is necessary to put them into a broader perspective. Firstly, it must be kept in mind that the excess costs of EU climate policy design are defined as additional cost compared to the scenario *uniform* which does not constitute a least-cost emission pricing strategy since our model includes initial market distortions such as various taxes. Secondly, the terminology "excess cost" in our context refers to a policy environment where we only pursue an emission reduction target but do not go for additional policy targets. Thirdly, our quantitative estimates hinge on the model assumptions of PACE together with the baseline projections provided by IEO. In the extreme, one could imagine that some other model and baseline may generate for scenario *uniform* the administered exogenous EU emission split between ETS and non-ETS sectors as an endogenous outcome together with a level for renewable energy which again corresponds to the current EU prescriptions – in such a case, the excess costs were zero as the exogenous policy constraints on emission market segmentation and RPS do not become binding.

5. Implications of Alternative Baseline Projections

Standard CGE analysis quantifies the impact of policy interference with respect to a reference situation where this interference is not in place – the so-called business-as-usual or benchmark equilibrium. Policy impact assessment then involves (i) changes in parameters or exogenous variables that reflect policy interference, (ii) simulation of the new counterfactual equilibrium, and (iii) comparison of the counterfactual and the benchmark equilibrium to derive information on policy-induced changes of economic variables. If policy targets and measures refer to the future there is the

[13] Note that in 2020 imposition of an RPS on top of a comprehensive EU emission trading scheme does not induce additional cost. There are various reasons for this: (i) scenario *uniform* pushes green power close to the target RPS level, (ii) supply elasticities of green power increase over time such that a smaller subsidy is warranted to achieve a given increase in green power supply, and (iii) there are initial tax distortions that are ameliorated through green subsidies.

need to establish a future business-as-usual capturing the evolution of the economy in the absence of these additional targets and measures.

The EU has formulated its climate policy target with respect to 2020, i.e. more than a decade from now, where the EU-wide greenhouse gas emissions shall be reduced by at least 20 % compared to 1990 emission levels. Obviously, baseline projections on future GDP and energy demands with associated emissions will have a major impact on the economic costs of EU climate policy. The baseline projections do not only determine the magnitude of the effective abatement requirement (the difference between the future business-as-usual emissions and the exogenous emission ceiling) but also the ease of emission abatement (the curvature of marginal abatement costs) and the consequences of initial market distortions. It is clear that a higher economic growth path together with higher emissions will c. p. induce higher compliance costs and, in turn, economic recession may reduce climate policy cost.

The critical importance of baseline projections is not very well elaborated in the public climate policy debate – even though the ongoing world-wide financial crisis provides a prime example of how instable projections for future economic growth and baseline emissions can be. We therefore perform a sensitivity analysis on the implications of alternative baseline projections for the costs of EU climate policy.

5.1. Alternative Baseline Projections

For our sensitivity analysis on alternative baseline projections we start with additional IEO views on future economic growth and associated CO_2 emissions: Beyond a reference variant (*ref*) the IEO features a high macroeconomic growth variant (*high_gdp*) and a low macroeconomic growth variant (*low_gdp*). The two alternative growth variants adopt different assumptions about future economic growth paths, while maintaining roughly the same relationship between changes in GDP and changes in energy consumption that is used in the reference case. In the high economic growth variant, 0.5 percentage points are added to the growth rate assumed for each country or country grouping; in the low economic growth case, 0.5 percentage points are subtracted from the reference case growth rate. In addition to the three standard IEO growth variants, we add two further growth variants that reflect the current global economic crisis and associated pessimistic expectations on economic performance: In variants *low50* and *low25* we use variant *ref* as the default but presume that country-specific growth rates between 2005 and 2010 are only 50 % or 25 % of the initially projected *ref* levels; the growth rates reach the original *ref* growth projections for 2015 and 2020 with a linear interpolation of growth rates between 2010-2015 based on the recession values for the time interval 2005-2010 and the reference values of the *ref* variant for the time interval 2015-2020. With respect to emission projections for our recession variants *low50* and *low25* we build on the assumption of the IEO that emission/GDP intensities are roughly the same across all baseline variants but these intensities decline along time reflecting autonomous energy efficiency improvements. It should be noted that the sensitivity analysis along the data and assumptions of the IEO mainly focus on the scale dimension of economic growth rather than alternative dynamics of structural change (for which no additional projections are available). Even so, the CGE baseline calibration to these alternative projections will alter both the overall effective reduction requirement as well as the marginal abatement cost curves across sectors.

Figure 6 depicts projected GDP growth for the EU across our five baseline variants between 2005 and 2030 (with GDP in 2005 indexed to 1). The recession variants stand out for substantially lower GDP at the end of 2010 reflecting the dramatic decline in EU economic activity since the beginning of the financial crisis in 2008. Growth rates later on align with the *ref* values but it is not before 2025 that the GDP in *low50* will have recovered to the level of the IEO *low_gdp* projection.

Figure 6: Baseline projections for economic growth of EU-27 (2005=1)

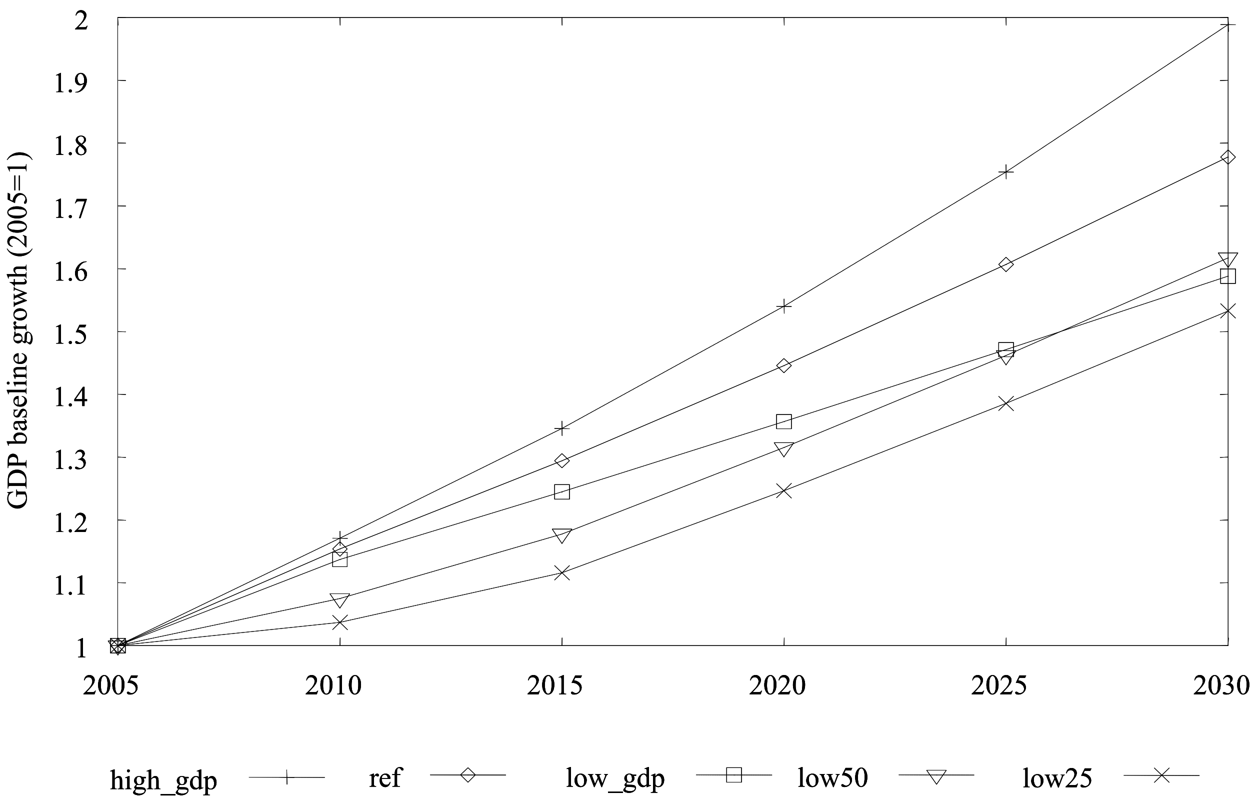
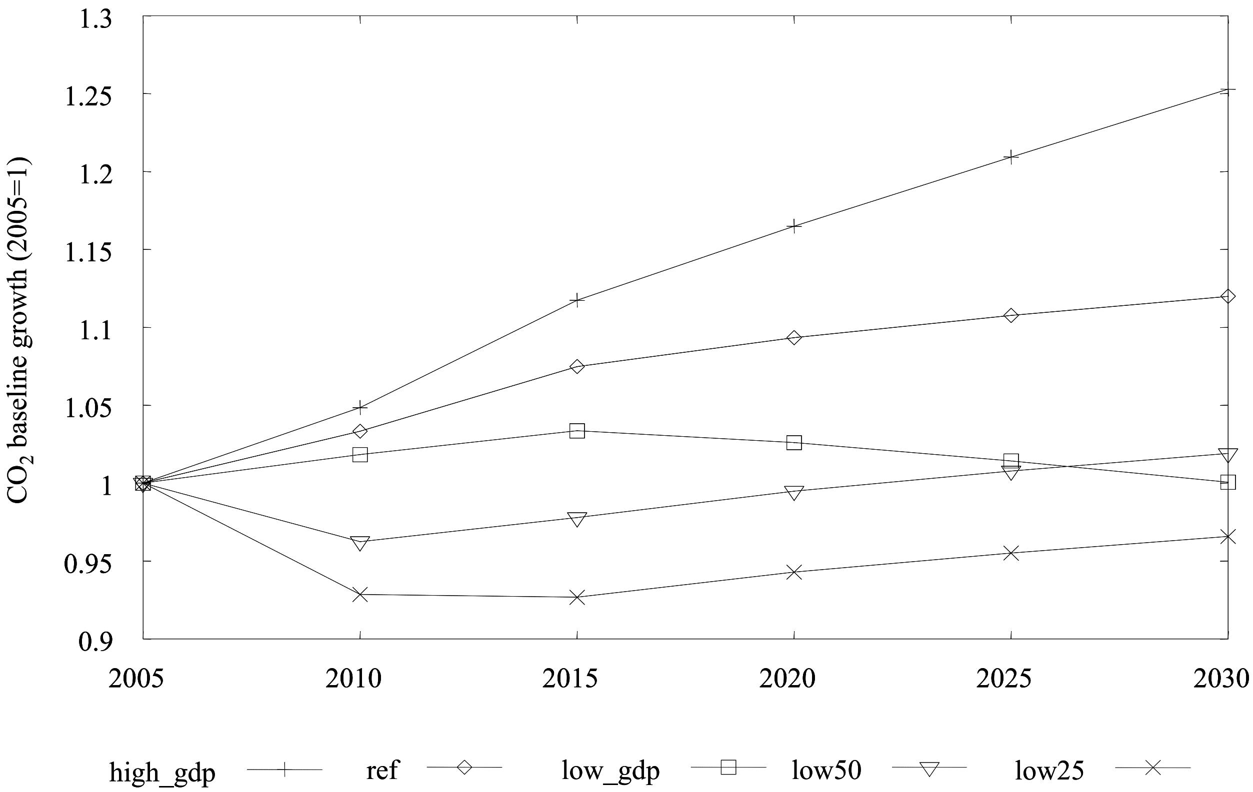


Figure 7 displays the associated CO_2 emission profiles for the EU: The implicit assumption of IEO expert projections is that emission/GDP intensities are roughly the same across all baseline variants but these intensities decline substantially along time. Total emissions may therefore decrease if GDP growth is not sufficiently high to offset the decrease in emission intensities. Figure 7 reveals substantial differences in the CO_2 emission baselines. In 2020 – the target year of the EU climate policy package – projected emissions are roughly 17 % above the 2005 level for variant *high_gdp* and around 5 % below the 2005 level for variant *low25*.

Figure 7: Baseline projections for CO_2 emissions of EU-27 (2005=1)



5.2. Forward-Calibration Technique

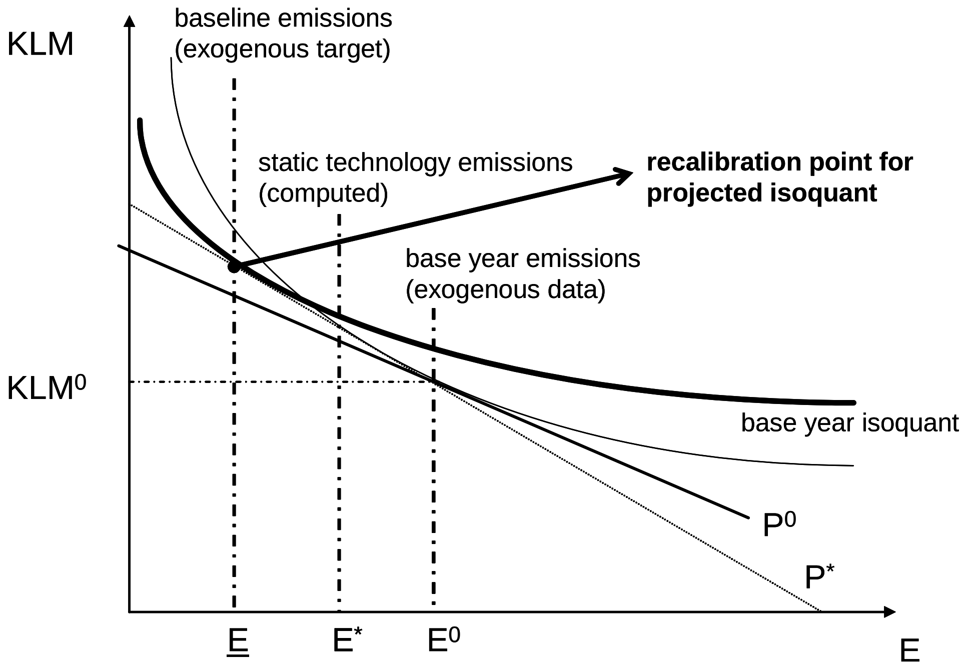
For our sensitivity analysis on alternative baseline projections, we need to target different exogenous business-as-usual emission levels that are associated with alternative projections on future GDP growth rates, fossil fuel supply prices, and energy demand by end-use sectors. To this end, we implement a simple but effective procedure for recalibration of cost and expenditure functions. The key idea is that – in the absence of more detailed information about off-the-steady-state economic changes – we want to keep the recalibrated functions in targeted energy demands as close as possible to the initial static technologies and preferences underlying the base-year calibration.

Figure 8 illustrates the basic methodology along a CES technology which is characterized by the continuous trade-off between energy (emission) inputs E and a composite non-energy input KLM. In calibrated share form the CES technology is fully described by reference demand quantities E^0 and KLM^0, the reference price ratio p^0 and an exogenous elasticity of substitution σ. Along the baseline growth path, we take potential GDP and fossil fuel supply prices (denominated in terms of a consumption price index) as exogenous while computing all other variables as equilibrium values.[14] This yields the energy/emission demand E^* together with a consistent equilibrium price ratio p^*.

[14] Note that we use the potential GDP growth rates to scale factor endowments and exogenous base year demands such as government demand. The exogenous fossil fuel prices are met through the endogenous rationing of fossil fuel supplies. The latter are later on recalibrated in consistency with empirical estimates on fossil fuel supplies.

However, the exogenous projections require baseline energy (emission) demand to match $\underline{E}$. We therefore impose $\underline{E}$ as re-calibrated reference demand at the new reference price ratio p^* and adjust reference demand quantities for KLM to be consistent with the isocost-line. After a few iterations this procedure yields a projected isoquant in exogenous energy/emission demands and residual other demands thereby warranting micro-consistency of economic adjustments as much as possible.[15]

Figure 8: Calibration to exogenous emission projections



5.3. Results

In the core simulations of section 4 we have adopted the EU's emission budget split between ETS and non-ETS sectors to investigate the excess costs of market segmentation vis-à-vis a comprehensive cap and trade system. The results are then driven by the huge discrepancy between the exogenous EU market split and the endogenous partitioning associated with uniform pricing (variant *ref*) in the PACE model. For the baseline sensitivity analysis, we want to focus more narrowly on the cost implications of changes in projections starting from an emission market split which coincides with uniform emission pricing in the PACE model. In other words: We use the PACE model jointly with the IEO reference baseline to determine the emissions of the ETS and non-ETS sectors under uniform emission pricing and then impose this split for the climate policy variants with market segmentation. For the sake of transparency and without loss of general insights, we drop the results presentation for those scenarios that deal with overlapping regulation and restrict ourselves to the comparison between

[15] At the recalibration point for the projected isoquant, the quantity of E is taken as exogenous whereas the quantities for KLM and the new reference prices are endogenously determined.

climate policy scenarios *uniform* (comprehensive emission market) and *ets* (segmented emission market).[16]

Figure 9 translates the EU emission reduction target of 20 % by 2020 vis-à-vis 1990 into the effective EU-wide emission reduction requirements from 2020 baseline emission levels (see label "Total"). The effective cutback requirements range from 11 % for the recession variants *low25* up to 28 % for the high growth variant *high_gdp*. Figure 9 furthermore shows the differential reduction requirements for the ETS and non-ETS sectors under hybrid regulation *ets* when we impose the emission allocation between ETS and non-ETS sectors derived from scenario *uniform* under the reference baseline variant (*ref*). This emission allocation implies markedly higher emission reduction requirements for ETS sectors than for non-ETS sectors thereby reflecting the cheaper emission reduction possibilities in the ETS sectors (see Figure 2). As we keep the differential emission reduction requirements from baseline variant *ref* but run into an economic recession the effective reduction requirements for the non-ETS sectors may even drop to zero or below (the latter indicating "hot air" in the non-ETS sectors).

Figure 10 reports how deviations from the reference baseline affect marginal abatement costs both for the case of uniform emission pricing (scenario *uniform*) as well as for differential emission pricing under hybrid regulation (scenario *ets*). Note that for the reference baseline the economy-wide emission price of scenario *uniform* must coincide with the emission prices in the ETS and non-ETS sectors of scenario *ets*. Obviously, marginal abatement costs go up with the increase in emission reduction requirements both at the economy-wide level as well as in the ETS and non-ETS sectors.

The further out we are on the marginal abatement cost curves the more expensive becomes an additional unit of abatement. The scale between ETS prices and non-ETS prices for hybrid regulation reverses as we move from lower to higher growth projections in comparison to the reference growth path: While for lower growth the emission prices in ETS are higher than those for non-ETS, the opposite applies for higher growth. The reasoning behind is provided by the much steeper marginal abatement cost curve for the non-ETS sectors (see Figure 2).

Figure 11 summarizes the total cost implications. As expected, more pessimistic projections on future economic activity associated with lower effective emission cutback requirements imply smaller economic adjustment cost. This intuitive result holds across all climate policy scenarios (note that for baseline variant *ref* the compliance costs for scenarios *uniform* and *ets* must be equal by definition).

Uncertainties on the future economic development captured through our set of alternative baseline variants may explain drastic differences in compliance cost (in our case by a factor 4 up to 6 depending on the baseline variant). In view of the actual turbulences of the global economy and rather uncertain growth prospects over the next years our results advice caution against single-point estimates on EU compliance cost.

[16] We underline the scenario label *ets* within the sensitivity analysis to recall that its partitioning of the EU-wide emission budget is different from that of scenario *ets* in the core simulations.

Figure 9: Effective emission cutback requirements in 2020 (% from baseline emission level)

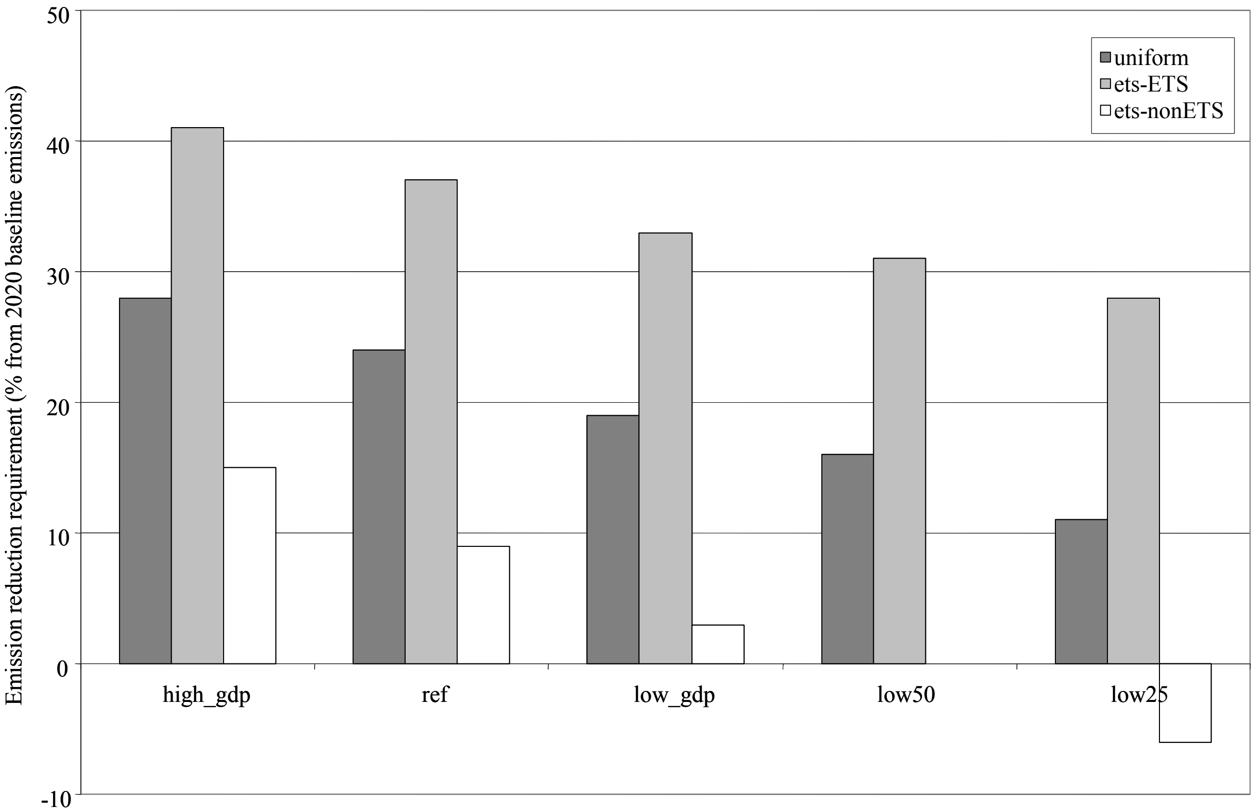


Figure 10: Marginal abatement costs in 2020 (€ per metric ton of CO_2)

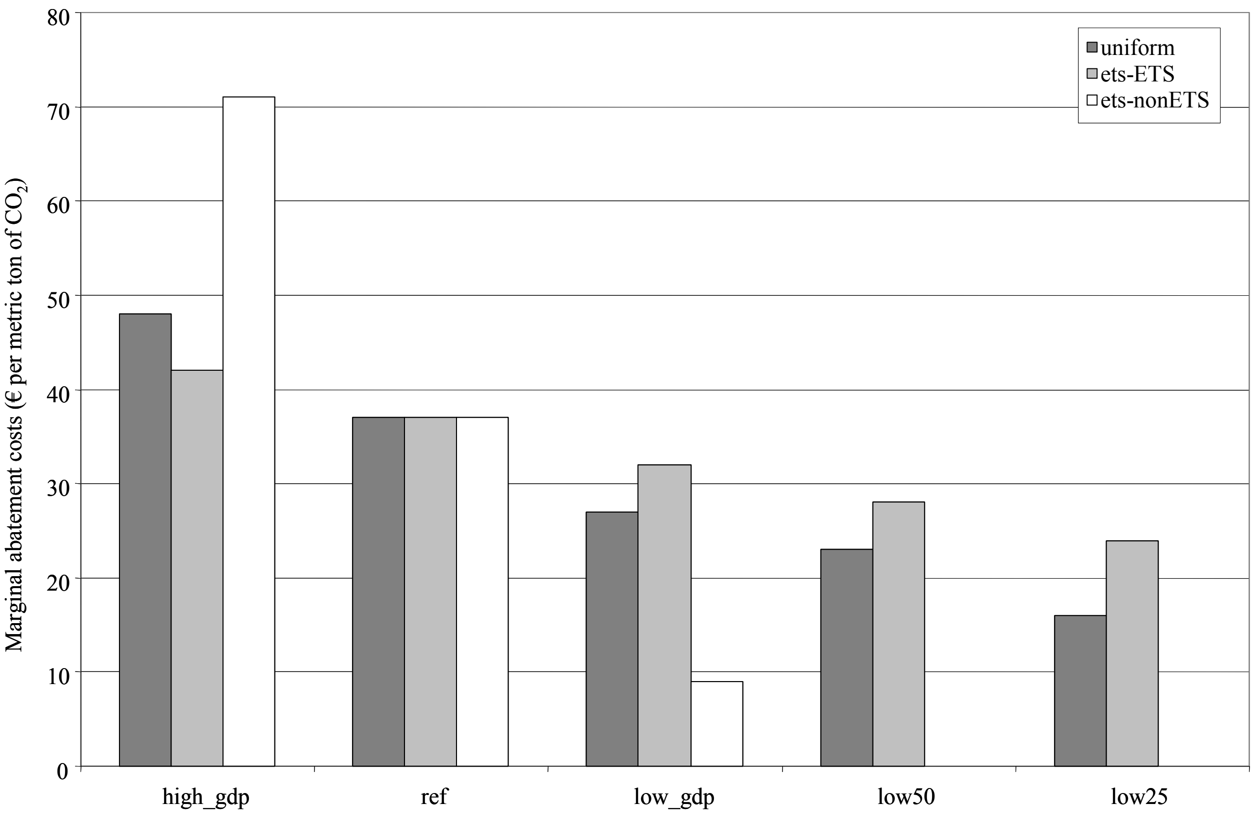


Figure 11: Compliance costs in 2020 (% HEV)

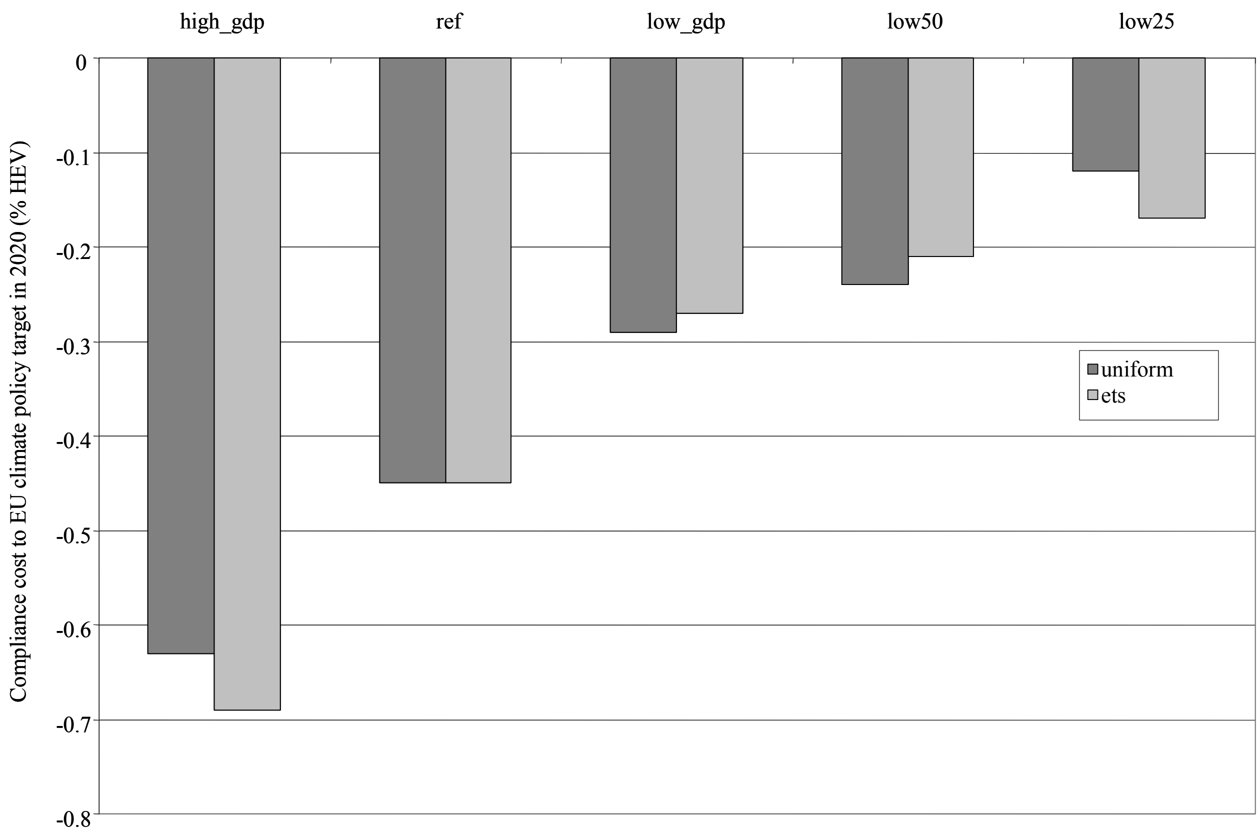


Figure 12: Excess costs of hybrid EU climate policy in 2020 (% of uniform pricing case)

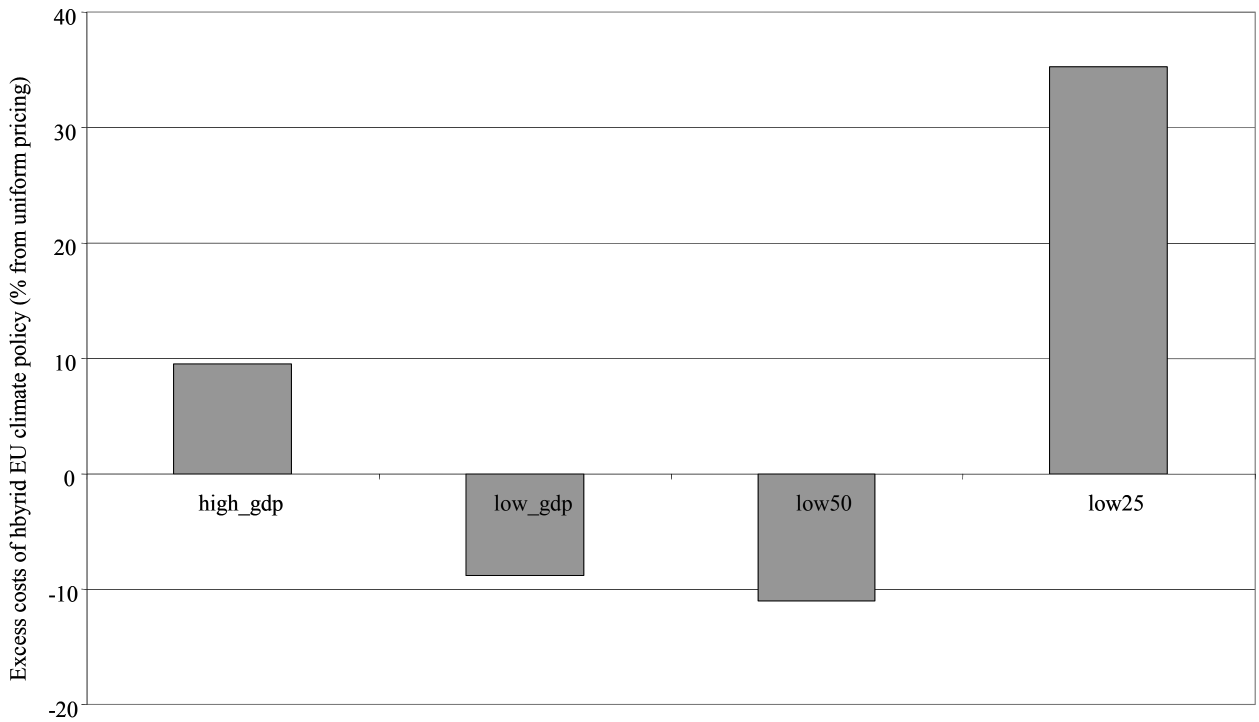


Figure 11 provides an example of the challenges involved in applied climate policy analysis when initial distortions and market imperfections are at work. As private and social marginal abatement costs diverge, differential emission pricing can push the economy closer to a second-best climate policy than uniform pricing: In our illustrative simulations we observe that for the less pronounced recession variant (*low50*) uniform emission pricing is more expensive than differential emission pricing whereas for the more severe recession variant (*low25*) it is the other way round. Figure 12 restates the potential importance of second-best effects in terms of excess costs from differential emission pricing over uniform pricing. In our model framework there are two sources for second-best effects: Firstly, we incorporate a broader set of initial distortionary taxes. Whenever differential emission pricing works against the initial tax distortions, there is the possibility that the additional direct abatement costs (as compared to uniform emission pricing) are more than offset through indirect efficiency gains from the alleviation of initial tax distortions. Secondly, in our global trade model there is scope for substantial terms-of-trade effects due to the common Armington assumption of product heterogeneity (i.e. domestic and foreign goods of the same variety are distinguished by origin). Large open economies may want to adopt differential emission pricing in order to improve their terms of trade and shift domestic abatement costs to other countries (see e.g. Krutilla, 1991).

In our second-best setting robust conclusions on the efficiency merits of uniform emission pricing would require extensive additional analysis that goes beyond the scope of the present paper. Not only is there the need for some analytical decomposition of the relative importance of different sources for second-best effects (in our case: various taxes on production, consumption, exports and imports as well as product heterogeneity in international trade). One also must perform comprehensive sensitivity analysis with respect to the local dependency of second-best implications on benchmark data, elasticities, or the stringency of policy shocks. For our investigation of alternative baselines, we have constrained ourselves to variations in the emission reduction target. As we increase the latter, we find that towards higher emission reduction targets it becomes more important to equalize marginal abatement costs. In other words: With a more ambitious climate policy, the first-best rule for emission abatement becomes more reliable because cost savings from uniform pricing outperform potential second-best gains from differential emission pricing.

5. Conclusions

In its “fight against climate change” the European Union (EU) pursues a unilateral greenhouse gas emission reduction target of 20 % from 1990 emission levels by 2020. In order to achieve this target, the EU builds on an EU-wide CO_2 cap-and-trade system for energy-intensive installations (ETS sectors) and additional measures by each EU Member States covering emission sources outside the cap-and-trade system (the non-ETS sector). Without emissions trading between the ETS sectors and the non-ETS sector EU policy has segmented the overall EU emission market into (at least) two segments. Furthermore, the EU has launched additional policy measures such as renewable portfolio standards to promote compliance with the climate policy target.

Simple first-best economic reasoning suggests that emission market segmentation and overlapping regulation are likely to create substantial excess costs if we focus on the climate policy target only. In our numerical impact assessment of the EU climate policy based on the PACE model and the reference baseline provided by the International Energy Outlook we find that in particular the segmentation of the EU emission market may cause substantial additional costs as compared to uniform emission pricing through a comprehensive EU-wide cap-and-trade system. The EU repeatedly has defended the hybrid emission market regulation for ETS and non-ETS sectors with drastic transaction costs should the millions of emitters belonging to the non-ETS sectors be included in the ETS cap-and-trade system. However, this view neglects the fact that with the transition of emission allocation from grandfathering towards auctioning a comprehensive cap-and-trade system for CO_2 emissions could be relatively easy implemented upstream through a few major oil, gas, and coal companies. Another legitimate claim in this context is the promotion of emission trade links between ETS and non-ETS sectors to assure that the direct cost of abatement will be lowered. In our actual model parameterization, the costs of overlapping regulation through renewable targets in the electricity sector seem modest since the future EU ETS pushes power generation close to the requested renewable portfolio standard. More detailed analysis on the potential excess cost of ambitious economy-wide targets for renewables or extensive energy efficiency programs envisaged under the EU Energy and Climate Policy Package is warranted. In any case, policy makers should be more explicit on the economic benefits they strive for with additional policy instruments such as generous renewable subsidies: Within the EU ETS subsidized renewable power production has no impact on emissions and arguments such as increased energy security or strategic technological innovation must be substantiated on scientific terms to gain credibility.

Our sensitivity analysis on future economic development recalls the importance of baseline assumptions on economic growth and energy demands for the compliance cost to future emission constraints – an issue which is often neglected in the public policy debate. Given substantial uncertainties on the economic future, a sensible range of alternative baseline projections should be examined to come up with a robust interval on the costs of EU emission abatement. Our numerical results indicate that the unforeseen recession may lower the EU compliance cost to a fraction of what would be due for the case of an optimistic economic outlook which has been the default assumption so far.

Our numerical analysis touches upon a fundamental challenge of applied climate policy analysis based on empirical data and actual market conditions. In the presence of substantial market distortions such as initial taxes or market power there is scope for substantial differences between private and social marginal abatement costs. As a consequence the clear-cut policy advice against differential emission pricing or overlapping regulation may no longer hold and our numerical simulations illustrated this point. If differential emission pricing or/and overlapping regulation can sufficiently ameliorate initial distortions then the direct excess cost from a first-best perspective can be more than offset through indirect efficiency gains on initial distortions. However, this insight should not be construed as a *carte blanche* for arbitrary policy design but rather as an impetus for thorough assessment of initial market distortions and their potential implications. The analytical derivation of second-best policies, however, is not tractable if we account for the dimensionality and complexity of applied policy analysis. Numerical simulations guided by theoretical arguments can provide useful insights into the relative importance of various determinants for second-best effects and their implications for climate policy design. Sorting out systematically the trade-offs between first-best rules and the potential gains from differential rules to exploit second-best effects in the context of EU climate policy is however a very complex task which we leave to future research.

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Appendix: Algebraic Model Summary

The computable general equilibrium model 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.3 provide a graphical exposition of the production structure.

Zero Profit Conditions

1. Production of goods except fossil fuels ($g \notin FF$):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{M} p_{gr}^{M(1-\sigma_{gr}^{KLEM})} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{E} p_{gr}^{E\,(1-\sigma_{gr}^{KLE})} + \left(1-\theta_{gr}^{E}\right) p_{gr}^{KL(1-\sigma_{gr}^{KLE})} \right]^{(1-\sigma_{gr}^{KLEM})/(1-\sigma_{gr}^{KLE})} \right]^{1/(1-\sigma_{gr}^{KLEM})} \leq 0$$

2. Sector-specific material aggregate:

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN} p_{igr}^{A\ 1-\sigma_{gr}^{M}} \right]^{1/(1-\sigma_{gr}^{M})} \leq 0$$

3. Sector-specific energy aggregate:

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

4. Sector-specific value-added aggregate

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v^{(1-\sigma_{gr}^{KL})} + \left(1-\theta_{gr}^{K}\right) w^{(1-\sigma_{gr}^{KL})} \right]^{1/(1-\sigma_{gr}^{KL})} \leq 0$$

5. Production of fossil fuels ($g \in FF$):

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

6. Armington aggregate:

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

7. Aggregate imports across import regions:

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

Market Clearance Conditions

8. Labour:

$$\bar{L}_{r} \geq \sum_{g} Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_{r}}$$

9. Capital:

$$\bar{K}_{gr} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_{gr}}$$

10. Fossil fuel resources ($g \in FF$):

$$\bar{Q}_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}}$$

11. Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}}$$

12. Energy composite:

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

13. Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}}$$

14. Import composite:

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

15. Armington aggregate:

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

16. Commodities (*g=i*):

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

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

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

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

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

19. Investment (*g=I*):

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

20. 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*
M_{gr}	Material composite for item *g* in region *r*
E_{gr}	Energy composite for item *g* in region *r*
KL_{gr}	Value-added composite for item *g* in region *r*
A_{igr}	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*
IM_{ir}	Aggregate imports of commodity *i* and region *r*

Table A.3 Price variables

p_{gr}	Price of item *g* in region *r*
p^{M}_{gr}	Price of material composite for item *g* in region *r*
p^{E}_{gr}	Price of energy composite for item *g* in region *r*
p^{KL}_{gr}	Price of value-added composite for item *g* in region *r*
p^{A}_{igr}	Price of Armington good *i* for demand category (item) *g* in region *r*
p^{IM}_{ir}	Price of import composite for good *i* in region *r*
w_{r}	Price of labour (wage rate) in region *r*
v_{ir}	Price of capital services (rental rate) in sector *i* and region *r*
q_{ir}	Rent to fossil fuel resources in region *r* ($i \in$ FF)
$p^{CO_2}_{r}$	Carbon value in region *r*

Table A.4 Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labour endowment for region *r*
$\overline{\mathrm{K}}_{\mathrm{ir}}$	Capital endowment of sector *i* in 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

$\theta_{\mathrm{gr}}^{\mathrm{M}}$	Cost share of the material composite in production of item *g* in region *r*
$\theta_{\mathrm{gr}}^{\mathrm{E}}$	Cost share of the energy composite in the aggregate of energy and value-added of item *g* in region *r*
$\theta_{\mathrm{igr}}^{\mathrm{MN}}$	Cost share of the material input *i* in the material composite of item *g* in region *r*
$\theta_{\mathrm{igr}}^{\mathrm{EN}}$	Cost share of the energy input *i* in the energy composite 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*
$\theta_{\mathrm{gr}}^{\mathrm{Q}}$	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*
$\theta_{\mathrm{igr}}^{\mathrm{A}}$	Cost share of domestic output *i* within the Armington item *g* of region *r*
θ_{isr}^{M}	Cost share of exports of good *i* from region *s* in the import composite of good *i* in region *r*

Table A.6 Elasticities

σ_{gr}^{KLEM}	Substitution between the material composite and the energy-value-added aggregate in the production of item *g* in region *r*[*]
σ_{gr}^{KLE}	Substitution between energy and the value-added nest of production of item *g* in region *r*[*]
σ_{gr}^{M}	Substitution between material inputs within the energy composite in the production of item *g* in region *r*[*]
σ_{gr}^{KL}	Substitution between capital and labour within the value-added composite in the production of item *g* in region *r*[*]
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in the production of item *g* in region *r* (by default: 0.5)
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_{ir}^{A}	Substitution between the import composite and the domestic input to Armington production of good *i* in region *r*[**]
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good *i* in region *r*[**]

[*]see Okagawa and Ban (2008) [**]see Badri and Walmsley (2008)

Figure A.1 Nesting in non-fossil fuel production

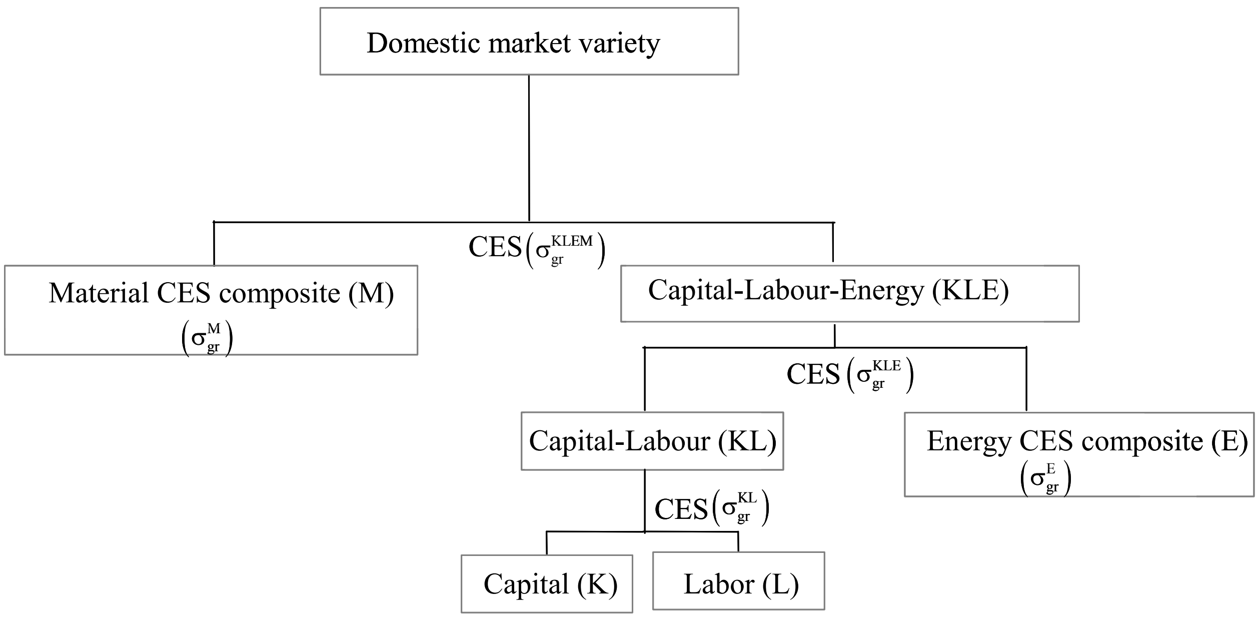

Figure A.2 Nesting in fossil fuel production

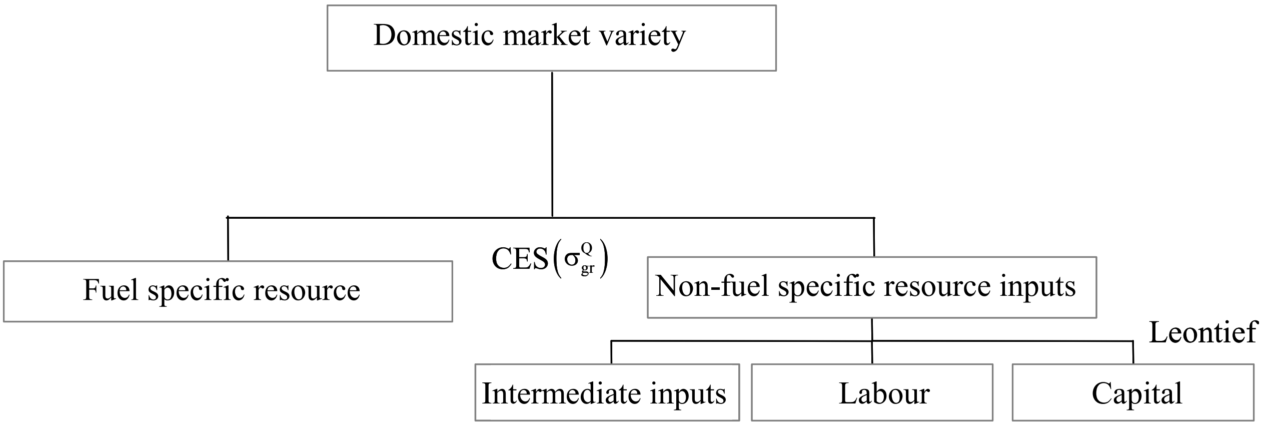

Figure A.3 Nesting in Armington production