Oldenburg Discussion
Papers in Economics

Clean-Development Investments:
An Incentive-Compatible CGE Modelling Framework

Christoph Böhringer
Thomas F. Rutherford
Marco Springmann

V – 354 – 13

March 2013

Department of Economics
University of Oldenburg, D-26111 Oldenburg

Clean-Development Investments:
An Incentive-Compatible CGE Modelling Framework

Christoph Böhringer[a], Thomas F. Rutherford[b], Marco Springmann[c]

[a] University of Oldenburg, Germany; E-mail: christoph.boehringer@uni-oldenburg.de

[b] University of Wisconsin-Madison, USA, E-mail: rutherford@aae.wisc.edu

[c] University of Oldenburg, Germany, E-mail: marco.springmann@uni-oldenburg.de

Abstract

The Clean Development Mechanism (CDM) established under the Kyoto Protocol allows industrialized Annex I countries to offset part of their domestic emissions by investing in emissions-reduction projects in developing non-Annex I countries. We present a novel CDM modelling framework which can be used in computable general equilibrium (CGE) models to quantify the sector-specific and macroeconomic impacts of CDM investments. Compared to conventional approaches that mimic the CDM as sectoral emissions trading, our framework adopts a microeconomically consistent representation of the CDM incentive structure and its investment characteristics. In our empirical application we show that incentive compatibility implies that the sectors implementing CDM projects do not suffer, and that overall cost savings from the CDM tend to be lower than suggested by conventional modelling approaches.

Keywords: Clean Development Mechanism, Computable General Equilibrium Modeling

JEL: C68, Q58

Acknowledgements: We are indebted to Govinda R. Timilsina for fruitful research cooperation within the World Bank Project ‘‘Low Carbon Economic Growth Opportunities in Developing Countries’’. The ideas expressed here remain those of the authors who remain solely responsible for errors and omissions.

1. Introduction

The Clean Development Mechanism (CDM) established under the Kyoto Protocol allows industrialized Annex I countries to offset part of their domestic emissions by investing in emissions-reduction projects in developing non-Annex I countries.[1] At the 18th Conference of the Parties (COP 18) of the United Nations Framework Convention on Climate Change (UNFCCC) in Doha, 2012, governments have agreed on a second commitment period of the Kyoto Protocol which is intended to bridge the years from 2013 to 2020 until a global agreement on climate change might become effective. As a key flexibility mechanism under the Kyoto Protocol, the CDM will continue through the second commitment period and will therefore remain in place at least until the end of this decade.

In 2011, the UNFCCC has launched a high-level policy dialogue on the CDM to reflect on the experiences gained and how to position the mechanism going forward. Analysts note that since its inception the CDM has triggered significant investments in emissions reductions in developing countries (Gillenwater and Seres, 2011; World Bank, 2011). However, the mechanism has also been subject to considerable criticism, e.g., on issues regarding the additionality of emissions reductions or the definition of the baseline against which those reductions are to be measured (see, e.g., Paulsson, 2009).

In this paper we abstract from the political and administrative discussions surrounding the CDM and instead focus on its economic impact assessment in numerical modelling studies.[2] From an economic perspective, the CDM addresses a fundamental efficiency pitfall inherent in the subglobal nature of current international climate policy agreements. Under the UNFCCC framework, only industrialized countries with relatively high marginal abatement costs have agreed to binding emissions reductions, while developing countries with relatively low marginal abatement costs have not adopted such targets.[3] This leaves a large potential for cost-effective emissions reduction in developing countries

---

[1] The CDM has two main purposes (Article 12.2 Kyoto Protocol). For Annex I countries its purpose is to increase the cost-efficiency of fulfilling their emissions reduction commitments made under the Kyoto Protocol by utilizing low-cost abatement options in non-Annex I countries. For non-Annex-I countries its purpose is to spur sustainable development by financing projects that reduce emissions and support development.

[2] A substantial body of literature has formed around the CDM analyzing and proposing ways to hold the CDM in line with its dual purpose of enabling cost-efficient (regionally flexible) emissions reduction for Annex I countries and of spurring sustainable development through CDM investment in non-Annex I countries (see, e.g., Ellis et al., 2007; Boyd et al., 2009; Lecocq and Ambrosi, 2007).

[3] The latest Conferences of the Parties in Copenhagen (COP-15), Cancún (COP-16), Durban (COP-17), and Doha (COP-18) have brought about only a voluntary pledge-and-review system. Although some developing countries, such as India and China, have contributed voluntary pledges, they have not adopted legally binding emissions-reduction commitments.

unexploited. The CDM attempts to increase the global cost-efficiency of subglobal abatement commitments by allowing part of industrialized countries' commitments to be met by undertaking emissions-reduction projects in developing countries.

Compared to previous approaches, our CDM modelling framework features a microeconomically consistent representation of the CDM incentive structure and its investment characteristics at the sector level which allows for a coherent evaluation of sectoral and economy-wide effects emerging from CDM investment decisions. Our proposed framework contributes to the literature in three ways. First, it allows for a more accurate economic impact assessment of the CDM. Second, it provides a clear distinction of the CDM mechanism compared to alternative regulatory climate policies that involve developing countries, such as integrated emissions trading. Third, our framework can be easily generalized to analyse other policy-relevant topics concerning clean-development investment, such as climate finance and green-growth strategies.

The remainder of this paper is organized as follows. Section 2 reviews previous CDM modelling approaches and discusses their shortcomings. Section 3 presents a stylized general-equilibrium model to document the implementation of our CDM modelling approach and highlight its differences to previous modelling approaches. Section 4 provides a stylized large-scale CGE application of the CDM implemented between the industrialized and the developing world. Section 5 concludes.

2. CDM modelling frameworks

There are two wide-spread modelling approaches for the quantitative assessment of economic impacts triggered by the CDM: bottom-up computable partial equilibrium (CPE) models and top-down computable general equilibrium (CGE) models. The two approaches differ mainly with respect to the emphasis placed on project-specific information vis-à-vis the comprehensiveness of economic responses.

CPE analyses of the CDM primarily focus on CDM supply options assessing costs and availability of project-based emission abatement in developing countries. For that purpose, analyses such as Jotzo and Michaelowa (2002) typically build on marginal abatement cost (MAC) curves which can be constructed from a variety of sources, such as project-level information (Wetzelaer et al., 2007), energy system models (Capros et al., 1998; Criqui et al., 1999), and general equilibrium models (Böhringer and Rutherford, 2002; Paltsev et al., 2005; Morris et al., 2012). Several studies, including Michaelowa and Jotzo (2005), Kallbekken (2007), or Böhringer and Löschel (2008), extend the simple MAC curve model to reflect transaction costs and investment risks associated with the project-based character of the CDM. CPE models can, depending on the data source, capture the discrete project nature of the CDM; however, they cannot represent the economy-wide impacts resulting from market interaction and income effects.

CGE models, on the other hand, contain a comprehensive representation of market interactions through price- and income-responsive supply and demand reactions. Beyond price-induced structural change in production and consumption, CGE models can quantify efficiency implications and distributional impacts of policy measures. The CDM is usually represented in CGE models as an integrated emissions-trading system (IET) where developing countries receive emissions permits in proportion to their business-as-usual levels and engage in trade with industrialized countries (see, e.g., Manne and Richels, 1999; Bernstein et al., 1999; MacCracken, 1999; Klepper and Peterson, 2005; Burniaux et al., 2009). By non-arbitrage, the CDM leads to a full equalization of marginal abatement costs (at the level of the endogenous permit price) across all sectors in the industrialized and the developing country that are covered by the IET.

Representing the CDM as an IET has, however, three major shortcomings. First, it may overstate the cost-savings potential of the CDM. As a more discrete, project-based mechanism the CDM is unlikely to capture all the cost-effective abatement options in production and consumption that would be ideally realized under an IET. Springer (2003) therefore describes this modelling approach as an optimistic version of the CDM. Addressing this issue, the EMF-16 impact study of the Kyoto Protocol (Weyant and Hill, 1999; see also Bernstein et al., 1999, and MacCracken, 1999) constrains the sale of CDM credits to 15% of the permit sales that would result under a full global emissions trading scheme. However, while such percentage-constraints are meant to capture the difficulties in the implementation of the CDM, they remain highly subjective (Manne and Richels, 1999).[4]

Second, the CDM representation as an IET is inconsistent with the incentive structure of the CDM. In particular, firms undertaking CDM projects are compensated for employing less emissions-intensive but more expensive production technologies through the sale of certified emission reductions – so-called CERs. In contrast, in an IET, firms face an emissions price on their inputs which increases their costs, while the revenues from CERs accrue to the region's representative agent or government.

[4] Another rather political than technical reasons for constraining the trade of emissions allowances between Annex I and non-Annex I countries is to represent the supplementarity requirement laid out in the Marrakech Accords to the Kyoto Protocol. Those accords state that the use of each of the flexible mechanisms (ETS, CDM, JI) shall be supplemental to domestic action and that domestic action shall thus constitute a significant effort made by each Party included in Annex I to meet its quantified emission limitation and reduction commitments. Supplementarity constraints are also part of various national climate policy strategies such as the EU Climate Action and Renewable Energy Package (EU, 2008).

Representing the CDM as a form of IET therefore leads to inconsistent sector-level impacts, including sectoral prices, production, and trade flows.

Thirdly, representing the CDM as an IET does not accommodate the CDM decision framework of the primary CDM market which entails an investment decision by those Annex I countries intending to buy CERs.[5] In an IET modelling framework the overall level of emissions reductions is the decision variable which endogenously yields the carbon price and the volume of permit trade. While this framework may accommodate the price-forming mechanism of the observable secondary CER market, it cannot capture the fundamental investment decisions that lead to the CDM project development in the contractual primary CER market.

3. An incentive-compatible CGE modelling framework for the CDM

Our CGE modelling approach addresses the above-mentioned shortcomings by representing the CDM in an incentive-compatible manner which reflects two key ideas of the CDM. First, firms will only engage in the CDM if they do not lose, suggesting that while they use more energy-efficient (and more expensive) production techniques, the firms are compensated such that their net production costs are unchanged. Second, CDM projects are bilateral agreements about "how much money" rather than about "how much carbon", i.e. countries demanding CDM credits decide on the amount of their CDM investment and take the CDM credits as an (endogenous) outcome of that investment. Our framework allows for a microeconomically consistent assessment of the CDM impacts at the sector and economy-wide levels.

We illustrate the CGE implementation of our approach within a stylized multi-region model of the global economy which can easily be adapted to more complex structures (see section 4 for a large-scale application). A comprehensive algebraic model formulation is provided in Appendix A and the programming source code in Appendix B. Here we present the equilibrium conditions that are required for the incentive-compatible representation of the CDM. In our stylized CGE model, macroeconomic production in each region takes place with inputs of capital, labour, and energy where

---

[5] In general, CDM buyers have two markets in which to purchase CERs, the primary and the secondary market (see, e.g., World Bank, 2005; Green, 2008). In the primary market, the investor and project developer agree on a price for the expected future credits from a CDM project. The resulting contract, which is known as an Emissions Reduction Purchase Agreement (ERPA), is similar to a project-finance agreement and can vary from case to case. The secondary CER (sCER) market is used for trading credits which are already delivered or with a guarantee of delivery or compensation if the contract is broken. In contrast to the primary market, the secondary one has an observable price (which is higher than the price in the primary CER market due to lower risks for the buyer).

a Cobb-Douglas composite of capital and labour trades off with energy at a constant elasticity of substitution (CES). We focus on a single sector-representing firm.

The default unit-cost function of the representative firm (sector) without participating in the CDM is given by:

$$C(p_E, p_L, p_K) = (\theta_E p_E^{1-\sigma} + \left(1 - \theta_E \left(p_K^{\vartheta} p_L^{1-\vartheta}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \qquad (1)$$

where p_E, p_L, p_K denote the prices of energy, labour, and capital, respectively; θ_E is the value share of energy inputs, ϑ the value share (output elasticity) of capital, and σ the elasticity of substitution between energy and the capital–labour composite.

CDM investments in the hosting representative firm (sector) can be represented as a combination of sectoral output subsidies and shadow emission taxes. The shadow emission taxes induce the adoption of more energy-efficient and more expensive production technologies, while the output subsidies compensate the representative firm in the CDM-hosting sector for the increase in production costs. Denoting the emission tax with τ and the output subsidy with μ, the unit-cost function of the firm participating in the CDM becomes:

$$C(\mu, \tau, p_E, p_L, p_K) = \frac{1}{1+\mu} (\theta_E (p_E(1+\tau))^{1-\sigma} + \left(1 - \theta_E \left(p_K^{\vartheta} p_L^{1-\vartheta}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \qquad (2)$$

Incentive compatibility implies that the CDM-hosting firm does not increase its cost of production. The arbitrage condition thus reads as[6]:

$$C(\mu = 0, \tau = 0, p_E, p_L, p_K) \geq C(\mu, \tau, p_E, p_L, p_K) \qquad (3)$$

The absolute level of CDM investment which is exogenously chosen by the CDM donor country (that demands the resulting CDM emissions offsets) provides the CDM budget constraint; the CDM investment transfer must cover the difference between subsidy payments and the implicit revenues from the shadow emission tax:

$$p_L T \geq \mu p_Y Y - \tau p_E E \qquad (4)$$

where p_Y and Y denote the price and quantity of output, p_E and E the price and quantity of energy.[7] We use p_L as a numéraire that translates the nominal CDM transfer level T into real terms.

[6] In the mixed complementarity formulation of our equilibrium model, this arbitrage condition is associated with the endogenous subsidy rate μ.

Our incentive-compatible CDM modelling approach differs in several respects from the commonly used IET representation.[8] First, the overall cost savings are lower than under IET because the scope for curbing emissions through output reduction in emission-intensive sectors of the CDM host country is limited due to the introduction of output subsidies. Second, the CDM-participating firms (sectors) in the CDM host country do not suffer from an increase in production cost. Third, the CDM transfers do not enter the budget of the representative agent in the CDM host country (as they are used for compensating the CDM-participating sectors via output subsides). Fourth, in contrast to the IET representation, there is no trade-induced price equalization of emission prices in the CER-demanding country (the CDM donor) and the prices for CDM offsets in the CDM host country.

4. Model application

We highlight the relevance of our CDM representation by means of a large-scale CGE application based on empirical data. For this purpose, we adopt a generic multi-region, multi-sector CGE model of global trade and energy use (see, e.g., Böhringer and Rutherford, 2002) calibrated to data of the Global Trade Analysis Project (GTAP). We compare the economic impacts of the CDM when represented either in our novel incentive-compatible approach or in the conventional IET manner. We first provide a non-technical summary of the basic model structure,[9] followed by information on the underlying GTAP database. We then lay out the policy scenarios and simulation results including sensitivity analysis for key parameters.

4.1. Model structure

Goods are produced with intermediate inputs and primary factors (labour, capital, and natural resources). Primary energy goods (crude oil, natural gas, and coal) exhibit decreasing returns to scale with respect to natural resource inputs which are sector-specific. Capital and labour are intersectorally mobile, but immobile across regions.

The production of energy and other goods is described by nested constant-elasticity-of-substitution (CES) cost functions which characterize substitution possibilities between inputs (see Figure 1). For all goods except fossil fuels, the CES cost functions are arranged in multiple levels. The top-level nest combines an aggregate of capital, labour, and energy inputs (KLE) with a composite of material inputs (M); the second-level nest combines an aggregate of energy inputs (E) with a value-added composite

---

[7] The CDM budget constraint is associated in complementarity with the shadow emission tax τ.

[8] The unit-cost function of the IET-type CDM representation is equivalent to Eq. (2) with the output subsidy rate set to zero ($\mu = 0$), and with the emissions price (τ) determined as the shadow price of the emissions cap of the multi-regional IET which includes the CDM-hosting countries (sectors).

[9] A more detailed technical description is provided in Böhringer and Rutherford (2011).

of capital and labour inputs (VA) in the KLE-nest, as well as non-energy material inputs (P(1) to P(N)) in the M-nest; the third level captures the substitution possibilities between capital (PK) and labour (PL) in the VA-nest, and the trade-off between electricity and a CES composite of fossil fuels (coal, refined oil, gas) (P(FE)) with their associated CO_2 emissions (PCARB) in the FE-nest.[10] The production of fossil fuels combines sector-specific fossil-fuel resources with an aggregate of all other inputs which enter in fixed proportions.

The representation of international trade follows Armington's (1969) approach of differentiating goods by country of origin: goods that satisfy domestic demand are represented as a CES aggregate of domestically produced goods and imported goods. A balance-of-payment constraint incorporates the base-year trade deficit or surplus for each region.

Final consumption in each region is determined by a representative agent who maximizes consumptions subject to its budget constraint. Consumption is represented as a CES aggregate of non-energy goods and energy inputs. The budget constraint is determined by factor and tax incomes with fixed investment and public expenditure.

4.2. Parameterization

As is customary in applied general-equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of the functional forms which characterize technologies and preferences. For this calibration we make use of data provided by the Global Trade Analysis Project (GTAP). The GTAP database (version 7,1) describes production, consumption, trade and CO_2 emissions from fossil-fuel combustion for up to 113 countries/regions, 57 commodities and 5 primary factors for the benchmark year 2004 (Narayanan and Walmsley, 2008). The GTAP database contains Armington trade elasticities and value-added elasticities. The elasticities of substitution in fossil-fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002).

For our illustrative economic impact assessment of the CDM, we aggregate the GTAP regions into two blocks: Annex I (AN1) countries which can invest in CDM projects and non-Annex I (NA1) countries which can implement CDM projects. With respect to commodities, the aggregation includes five energy goods (coal, natural gas, crude oil, refined oil, and electricity), an energy-intensive composite (including non-ferrous metals, non-metallic minerals, iron and steel, and chemical products), an aggregate transport good, and a composite of all other remaining goods and services.

[10] CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific fuels carbon content.

4.3. Model scenarios

We devise three model scenarios to illustrate the relevance of our incentive-compatible CDM framework. Those are a reference cap-and-trade scenario in which Annex I countries reduce their emissions without using the CDM, the commonly applied IET representation of the CDM, and our alternative incentive-compatible CDM representation.

The reference cap-and-trade scenario (*REF*) is designed as a ballpark characterization of current and contemplated climate policies. Therein, Annex I countries reduce their CO_2 emissions by 20% with respect to their benchmark emissions in 2004. This magnitude is indicative of possible short to medium-term emissions reductions (Levin and Bradley, 2010) and broadly in line with the pledges submitted to the Copenhagen Accord.

The *IET* scenario represents the CDM as an integrated emissions-trading system (see, e.g., Springer, 2003, Burniaux et al., 2009). Annex I countries are subjected to the same 20% emissions-reduction target as in the *REF* scenario, but they can now trade emission permits with non-Annex I countries which are allocated their benchmark(-2004) emissions.

The *ICC* scenario represents the CDM in the incentive-compatible framework presented above. Annex I countries can invest in CDM projects in non-Annex I countries and relax their domestic emissions target by the emissions reduced due to these projects. We determine the optimal level of CDM investment by iteratively optimizing the amount of CDM transfers with respect to its effect on Annex I countries' welfare.

To date, more than two thirds of all CDM projects have been implemented in the electricity sector (UNEP Risoe, 2012).[11] We mimic this situation by allowing CDM implementation in the electricity sector only. To ensure comparability, we also limit the integrated emissions-trading system in the *IET* scenario to the electricity sector.

We design the comparison between the *ICC* and *IET* representations of the CDM as a cost-effectiveness analysis in which global emissions are held constant at the emission level emerging from the reference scenario *REF*. This allows for a consistent welfare comparison across scenarios without the need to assess the monetary benefits of emissions reductions.

[11] Detailed information on the type of CDM projects can be found at http://www.cdmpipeline.org/cdm-projects-type.htm (accessed 05/27/ 2012).

4.4. Results

Figure 2 reports the welfare effects across our three core scenarios in terms of percentage changes in Hicksian equivalent variation of income. The reference cap-and-trade (*REF*) scenario results in welfare reduction in Annex I as well as in non-Annex I countries. The introduction of carbon pricing in Annex I countries increases domestic prices. This reduces consumption in Annex I countries and affects non-Annex I countries through reduced import demand and increased export prices. Thus, adjustment costs to unilateral emission constraints do not only occur in Annex I countries but spill over through adverse changes in the terms-of-trade to non-Annex I countries (Böhringer and Rutherford, 2002).

Allowing Annex I countries to meet part of their emissions reduction requirements through emissions offsets in the *IET* and *ICC* scenarios alleviates the negative welfare impacts of the *REF* scenario. Both CDM scenarios lead to similar relative cost savings of 52-60% for Annex I countries. However, their effect on non-Annex I countries differs significantly. The *IET* representation of the CDM yields distinctly larger relative cost savings for non-Annex I countries (86%) than the incentive-compatible *ICC* representation (59%). While the incentive-compatible *ICC* representation preserves the distribution of welfare impacts between Annex I and non-Annex I countries, the *IET* representation leads to disproportionally more welfare gains for non-Annex I countries than for Annex I countries.

The cost savings in the *IET* and *ICC* scenarios emerge from increased where-flexibility of emissions reduction through CDM offsets. Table 1 provides an overview of the key characteristics of the CDM for both "where-flexibility" scenarios. The IET scenario induces CDM transfers from Annex I to non-Annex I countries (in the form of payments for emissions allowances) of USD 17.6 billion, which yields CO_2 emissions offsets of about 1.2 Gt for Annex I countries. More than half of Annex I countries' emissions reduction commitment is met through CDM emissions permits. As a result of the inflow of emissions permits, the CO_2 price in Annex I countries decreases by 60%, from 36 USD/tCO2 to 14.5 USD/tCO2.

In comparison, the *ICC* scenario induces 35% less CDM transfers to non-Annex I countries (USD 11.5 billion) which yield 9% less emissions offsets for Annex I countries (1.1 $GtCO_2$). The decrease in Annex I countries' CO_2 price is slightly less pronounced in the *ICC* scenario than in the *IET* scenario. The CO_2 price in the *IET* representation is (by non-arbitrage in the integrated emissions-trading system) the same as the CER price. In contrast, the *ICC* scenario allows for price differentiation, with the CER price given by the ratio of CDM investment to the emissions reductions in non-Annex I countries that are brought about by the investment. The resulting CER price amounts to 10.4 USD/tCO_2 which is 32% lower than the CO_2 price in Annex I countries.

Figure 3 depicts the differences between the *IET* and *ICC* scenarios at the sector level. It highlights the price and output changes in the CDM-implementing electricity sector for the two scenarios relative to the *REF* scenario without “where-flexibility”. In the *IET* scenario, electricity prices in non-Annex I countries increase by 16.5% as a result of emissions pricing in the sectoral ETS implementation. As a consequence, electricity output falls by 9.2% in non-Annex I countries. At the same time, Annex I countries expand their electricity output by 4.9%, which mirrors the relative decrease in the domestic CO_2 price.

The *ICC* scenario yields qualitatively different results compared to those of the *IET* scenario. The prices and output of the CDM-implementing electricity sector remain effectively constant in the *ICC* scenario, which reflects the CDM incentive-compatibility condition that keeps the firm's unit cost of production unchanged from its reference level. The effects on Annex I countries’ electricity sector are similar to those in the *IET* scenario, but driven by the relative slighter decrease in CO_2 prices. As a result, the increase in Annex I countries’ electricity output is 0.6% lower in the *ICC* scenario compared to the *IET* one.

4.5. IET scenario with rebates

The inconsistent assessment of sectoral impacts in the *IET* scenario may be attenuated by changing the incentive structure of the CDM-implementing sector. Instead of auctioning emissions permits (with revenues retained by the representative agent in the CDM host region), we consider a scheme in which the sector participating in the CDM is compensated for the direct costs of emissions permits through output-based rebates (*IET_rb*). This variant differs from the incentive-compatible CDM formulation, because the sector participating in the CDM is not compensated to the extent that its unit costs of production are held constant at the *REF* level.

Figure 4 contrasts the sector-level effects and overall welfare impacts of the integrated emissions-trading scenario with rebates *(IET_rb*) with those of the standard *IET* scenario and the incentive-compatible *ICC* representation. In the *IET_rb* scenario, the price increases and output losses for the CDM-implementing electricity sector are significantly reduced compared to those in the standard *IET* representation, from 16.5% to 2.2% and from -9.2% to -1.4% respectively. However, the directional impacts still contrast with, and are opposed to, the price and output changes in the incentive-compatible *ICC* representation.

The welfare impacts between the scenarios show further divergences. In the *IET_rb* scenario, the welfare losses for Annex I countries increase by 21% and those for non-Annex I countries decrease by

46% compared to the standard *IET* representation.[12] The differences to the welfare effects of the incentive-compatible *ICC* scenario thus become even more pronounced in the *IET_rb* scenario.

4.6. Sensitivity analysis

We assess the robustness of our findings with respect to changes in key model parameters. Those are the fossil-fuel supply elasticities, the Armington-trade elasticities, and the emissions-reduction target. In our piecemeal sensitivity analysis we double (x2) or halve (:2) the fuel-supply (*esub_ff)* and Armington-trade elasticities (*esub_arm)* respectively, and we change the emissions-reduction target for Annex I countries from 20% to 10% and to 30%.[13]

In general, decreasing the fossil-fuel supply elasticities reduces the responsiveness of the fossil-fuel supply to demand reductions in the emissions-abating Annex I countries, so that a decline in international fuel prices becomes more pronounced. This benefits fuel importers and hurts fuel exporters. Higher Armington elasticities increase the trade responsiveness to price changes. This reduces the scope for shifting costs to trading partners and therefore increases the competitive disadvantages of energy-intensive industries operating in CO_2-pricing Annex I countries. Higher reduction targets for Annex I countries increase their domestic adjustment costs but also enhance adverse terms-of-trade spillovers to non-Annex I countries.

Table 2 indicates that the relative welfare and sector-level differences between *IET* and *ICC* are preserved for a wide range of elasticity parameters. The alternative parameter assumptions result in variations around the main scenarios' values with the following trends. First, halving the Armington elasticities increases the relative welfare differences between the *IET* and *ICC* scenarios for Annex I and non-Annex I countries (and vice versa). Second, changes in the fossil-fuel supply elasticities have little effect on the relative welfare differences between the model scenarios. Third, the negative output effects in the CDM-implementing sector in the *IET* representation are found in all sensitivity scenarios.

[12] Reasons for the effect on Annex I countries are that the CDM becomes less efficient with rebates granted to the electricity sector, as they work against emissions reductions. Reasons for the effects on non-Annex I countries are on the sector level as consumers in non-Annex I countries benefit from less drastic price increases for electricity compared to the standard representation.

[13] An emissions-reduction target in Annex I countries of 10% is broadly in line with the Kyoto Protocol's initial emissions-reduction target of 5.2% below 1990 levels (which correspond to reducing emissions by about 10% below 2004 levels). A target of 30% is closer to the range of emissions reductions (25% to 40% below 1990 levels) that are needed to stabilize global emissions at 450 ppm (see, e.g., Levin and Bradley, 2010).

Figure 5 focuses on the welfare effects of different emissions-reduction targets. Similar welfare effects are obtained in both CDM representations when Annex I countries adopt a low emissions-reduction target of 10%. However, a high emissions-reduction target of 30% yields qualitatively different results for each representation, in particular for non-Annex I countries. The incentive-compatible *ICC* representation maintains the distribution of welfare impacts between Annex I and non-Annex I countries, while the *IET* representation is associated with large welfare gains for non-Annex I countries which may even exceed the business-as-usual (pre-policy) level. Thus, while the *IET* and *ICC* representations of the CDM yield similar macroeconomic impacts for low emissions-reduction targets, the macroeconomic assessment of the two representations diverge as emissions-reduction targets become more stringent. For the sector-level analysis, the *IET* and *ICC* representations provide contrasting results across all emissions-reduction targets.[14]

5. Conclusion

The Kyoto Protocol, and with it the CDM, has entered its second, 7-year long commitment phase in 2013. Annex I countries can continue to meet part of their domestic emissions-reduction commitments through CDM investments and the resulting CDM emissions credits. An appropriate appraisal of the CDM calls for a coherent modelling framework to quantify its economic impacts and to compare the CDM with alternative policy options, such as the sectoral or full linking of emissions-trading systems between industrialized and developing countries.

This paper has presented an incentive-compatible CDM implementation for economy-wide CGE models. Our approach is based on two tenets. First, the firms implementing CDM projects are compensated for emissions-abatement costs in such a way that their unit costs of production remain unchanged. Second, the countries demanding CDM-based emissions offsets decide on the amount of CDM investment and receive emissions offsets as a return to that investment.

A comparison with the common modelling approach of representing the CDM as an integrated emissions-trading system (in which CDM host countries are allocated their benchmark emissions) shows several divergences. At the sector level, the common IET representation of the CDM results in increased prices in the CDM-implementing non-Annex I sector, which leads to decreases in output and exports. In contrast, prices and output in the CDM implementing non-Annex I sector remain roughly constant in our incentive-compatible CDM modelling approach. While the CO_2 price in Annex I countries equalizes with the price for CDM offsets in the IET representation, the incentive-

[14] The relative output changes between the IET and CDM scenarios in the CDM-implementing sector in non-Annex I countries (as defined in Table 2) are -4.1% and -14.4% for a 10% and 30% emissions-reduction target, respectively.

compatible CDM framework allows for price differentiation between the two prices. At the macroeconomic level, the cost savings for non-Annex I countries are significantly less pronounced in the incentive-compatible framework than in the IET representation, since CDM transfers are used in the former to compensate the firm/sector which is implementing CDM projects.

Despite of its advancements there are various aspects of the CDM which our incentive-based CDM representation still abstracts from. First, we impose that CDM hosting firms (sectors) must be compensated at their pre-CDM (reference) cost level. However, CDM-hosting firms might try to bargain for positive profits with CDM donors on the distribution of overall cost savings from the CDM – this would essentially call for a game-theoretic setting. Second, the top-down characterisation of sector-specific production possibilities through continuous functional forms cannot address the project-level characteristics of CDM but describes a sectoral CDM policy – to capture discrete projects one would have to include bottom-up activity analysis in the top-down CGE framework. Third, the representation of the CDM market is relatively crude and, while focussing on the primary CDM market, it does not make a distinction between the primary and secondary CDM markets. While we defer appropriate extensions to future research, we note that although our modelling approach has been analysed and presented with reference to the CDM, it can be generalized to other related issues, such as the impacts of climate finance and green-growth strategies.

References

Armington, P.S., 1969. A Theory of Demand for Products Distinguished by Place of Production. *International Monetary Fund Staff Papers* 16(1), 159–176.

Berstein, P.M., Montgomery, W.O., Rutherford, T.F., Yang, G.F., 1999. Effects of Restrictions on International Permit Trade, The MS-MRT Model. *The Energy Journal*, 20 (Special Issue), 221-256.

Böhringer, C. and Rutherford, T.F., 2002. Carbon Abatement and International Spillovers. *Environmental and Resource Economics*, 22 (3), 391-417.

Böhringer C., Rutherford, T.F., and Wiegard, W., 2003. Computable General Equilibrium Analysis: Opening a Black Box. ZEW Discussion Paper No. 03-56.

Böhringer, C. and Löschel, A., 2008. Climate Policy Induced Investments in Developing Countries: The Implications of Investment Risks. *The World Economy*, 31 (3), 367-392.

Böhringer, C., Carbone, J.C., and Rutherford, T.F., 2011. *Embodied carbon tariffs*. Working Paper 17376, National Bureau of Economic Research, Cambridge, MA.

Böhringer, C. and Rutherford, T.F., 2010. The Costs of Compliance: A CGE Assessment of Canada's Policy Options under the Kyoto Protocol. *The World Economy*, 33 (2), 177-211.

Boyd, E., Hultman, N., Roberts, J.T., Corbera, E., Cole, J., Bozmoski, A., Ebeling, J., Tippman, R., Mann, P., Brown, K., Liverman, D.M., 2009. Reforming the CDM for sustainable development: lessons learned and policy futures. *Environmental Science & Policy*, 12 (7), 820–831.

Burniaux, J. M., Chateau, J., Dellink, R., Duval, R., and Jamet, S., 2009. *The economics of climate change mitigation: How to build the necessary global action in a cost-effective manner* (No. 701). OECD Publishing, Paris.

Capoor, K. and Ambrosi, P., 2007. State and Trends of the Carbon Market 2009. World Bank, Washington DC.

Capros, P. et al., 1998. The PRIMES energy system model–reference manual. *National Technical University of Athens.*

Cottle, R.W., Pang, J.S., and Stone, R.E., 1992. The linear complementarity problem. Academic Press, New York.

Criqui, P., Mima, S., and Viguier, L., 1999. Marginal abatement costs of CO_2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model. *Energy Policy*, 27 (10), 585–601.

Ellis, J., Winkler, H., Corfee-Morlot, J., & Gagnon-Lebrun, F., 2007. CDM: Taking stock and looking forward. *Energy Policy*, *35* (1), 15-28.

EU, 2008. The Climate Action and Renewable Energy Package, Europe's climate change opportunity, available at: http://ec.europa.eu/environment/climat/climate_action.htm.

Gillenwater, M. and Seres, S., 2011. The Clean Development Mechanism: a review of the first international offset programme. *Greenhouse Gas Measurement and Management*, 1 (3-4), 179–203.

Graham, P., S. Thorpe and L. Hogan, 1999. Non-competitive market behaviour in the international coking coal market, *Energy Economics*, 21(3), 195-212.

Green, G.A., 2008. *A Quantitative Analysis of the Cost-effectiveness of Project Types in the CDM Pipeline*. Københavns Universitet, Det Biovidenskabelige Fakultet for Fødevarer, Veterinærmedicin og Naturresourcer, Fødevareøkonomisk Institut.

Krichene, N. ,2002. World crude oil and natural gas: a demand and supply model. *Energy Economics* 24 (6), 557-576.

Jotzo, F. and Michaelowa, A., 2002. Estimating the CDM market under the Marrakech Accords. *Climate Policy*, 2 (2), 179–196.

Kallbekken, S., 2007. Why the CDM will reduce carbon leakage. *Climate Policy*, 7 (3), 197–211.

Klepper, G., 2011. The Future of the European Emission Tradings System and the Clean Development Mechanism in a Post-Kyoto world. *Energy Economics*, 33 (4), 687–698.

Klepper, G. and Peterson, S., 2005. Emissions Trading, CDM, JI, and More - The Climate Strategy of the EU. FEEM Working Papers, No. 2005, 55.

Lecocq, F. and Capoor, K., 2005. *State and Trends of the Carbon Market, 2005*, World Bank, Carbon Finance Unit, Washington DC.

Lecocq, F. and Ambrosi, P., 2007. The Clean Development Mechanism: History, Status, and Prospects. *Review of Environmental Economics and Policy*, 1 (1), 134–151.

Levin, K. and Bradley, R., 2010. Comparability of Annex I emission reduction pledges. World Resources Institute Working Paper. World Resources Institute, Washington DC. MacCracken, C. N., Edmonds, J. A., Kim, S. H., and Sands, R. D., 1999. The Economics of the Kyoto Protocol. *The Energy Journal*, 20 (Special Issue), 25-72.

Manne, A. and Richels, R., 1999. The Kyoto Protocol: a cost-effective strategy for meeting environmental objectives, *The Energy Journal*, 20 (Special Issue), 1-24.

Mathiesen, L., 1985. Computation of economic equilibria by a sequence of linear complementarity problems. *Operations Research*, 33 (6), 1225-1250.

Michaelowa, A. and Jotzo, F., 2005. Transaction costs, institutional rigidities and the size of the clean development mechanism. *Energy Policy*, 33 (4), 511–523.

Morris, J., Paltsev, S., and Reilly, J., 2012. Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: results from the EPPA model. *Environmental Modeling and Assessment*, 1–12.

Narayanan, B.G. and Walmsley, T.L., 2008. Global trade, assistance, and production: the GTAP 7 data base. *Center for Global Trade Analysis, Purdue University*.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim, M. C., and Babiker, M. H., 2005. *The MIT emissions prediction and policy analysis (EPPA) model: version 4*. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA.

Paulsson, E., 2009. A review of the CDM literature: from fine-tuning to critical scrutiny?. *International Environmental Agreements: Politics, Law and Economics*, 9 (1), 63–80.

Rutherford, T.F., 1995. Extension of GAMS for complementarity problems arising in applied economic analysis. *Journal of Economic Dynamics and Control*, 19 (8), 1299–1324.

Springer, U., 2003. The market for tradable GHG permits under the Kyoto Protocol: a survey of model studies. *Energy Economics*, 25(5), 527–551.

US Energy Information Administration (US EIA), 2009. *International Energy Outlook 2009*. Publication & Information Sales.

Wara, M., 2007. Is the global carbon market working?. *Nature*, 445 (7128), 595–596.

Wetzelaer, B.J.H.W., van der Linden, N.H., Groenenberg, H., de Coninck, H.C., 2007, *GHG marginal abatement cost curves for the non-Annex I region*, Report ECN-E-06-060, Energy Research Center of the Netherlands (ECN), Petten.

World Bank, 2011. State and trends of the carbon market 2011. World Bank Group, Washington DC.

Appendix A. Algebraic model summary

Following Mathiesen (1985), Cottle and Pang (1992) and Rutherford (1995), an economic equilibrium can be expressed as a mixed complementarity problem where inequalities are associated with decision variables. 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. Furthermore, income balances keep economic agents on their budget lines. In the following, we state the equilibrium conditions for our stylized CGE model of section 3. Tables A1-A5 provide an overview of the symbols and notation used. For a convenient calibration of functional forms based on an initially balanced dataset we make use if the calibrated share form (see Böhringer et al., 2003). Numerically, the model is implemented in the general algebraic modelling system GAMS and solved using PATH.

Zero-profit conditions:

1. Macro output:

$$\left(\theta_r^E (p_r^{ED}(1+\tau_r))^{1-\sigma} + (1-\theta_r^E)\left(v_r^{\theta_r^K} w_r^{(1-\theta_r^K)}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \geq p_r^Y(1+\mu_r) \quad \perp \quad y_r \tag{5}$$

2. Energy:

$$\left(\theta_r^R v_r^{1-\eta} + (1-\theta_r^{ER}) q_r^{1-\eta}\right)^{\frac{1}{1-\eta}} \geq p^E \quad \perp \quad y_r^E \tag{6}$$

3. Energy demand:

$$p^E + p^{CO_2} \geq p_r^{ED} \quad \perp \quad y_r^{ED} \tag{7}$$

4. Armington aggregate (in final consumption):

$$\left(\sum_s \theta_{sr}^Y p_r^{1-\gamma}\right)^{\frac{1}{1-\gamma}} \geq p_r^A \quad \perp \quad y_r^A \tag{8}$$

5. Welfare (utility):

$$w_r^{\theta_r^{LW}} p_r^{A(1-\theta_r^{LW})} \geq p_r^W \quad \perp \quad y_r^W \tag{9}$$

Market-clearing conditions:

6. Output:

$$Y_r \geq \sum_s \overline{c_{rs}} A_s \left(\frac{p_s^A}{p_r^Y}\right)^{\gamma} \quad \perp \quad p_r^Y \tag{10}$$

7. Energy:

$$\sum_r y_r^E \geq \sum_r y_r^{ED} \quad \perp \quad p^E \tag{11}$$

8. Energy demand:

$$y_r^{ED} \geq \overline{ed_r} y_r \left(\frac{(1+\mu_r) p_r^Y}{(1+\tau_r) p_r^{ED}}\right)^{\sigma} \quad \perp \quad p_r^{ED} \tag{12}$$

9. Labor:

$$\overline{L_r} \geq \overline{ls_r} \frac{y_r^W p_r^W}{w_r} + \overline{l_r} y_r \left(\frac{p_r^Y (1+\mu_r)}{v_r^{\theta_r^K} w_r^{1-\theta_r^K}}\right)^{\sigma} \frac{v_r^{\theta_r^K} w_r^{(1-\theta_r^K)}}{w_r} \quad \perp \quad w_r \tag{13}$$

10. Capital:

$$\overline{K_r} \geq \overline{f_r} y_r^E \left(\frac{p^E}{v_r}\right)^{\eta} + \overline{k_r} y_r \left(\frac{p_r^Y (1+\mu_r)}{v_r^{\theta_r^K} w_r{}^{(1-\theta_r^K)}}\right)^{\sigma} \frac{v_r^{\theta_r^K} w_r^{(1-\theta_r^K)}}{v_r} \quad \perp \quad v_r \tag{14}$$

11. Fossil-fuel resources:

$$\overline{Q_r} \geq \overline{Q_r} y_r^E \left(\frac{p^E}{q_r}\right)^{\eta} \quad \perp \quad q_r \tag{15}$$

12. Armington:

$$\sum_s c_{sr}\, y_r^A \geq \sum_s c_{sr}\, y_r^W \frac{p_r^W}{p_r^A} \quad \perp \quad p_r^A \tag{16}$$

13. Welfare:

$$y_r^W \left(\sum_s c_{sr} + \overline{ls_r}\right) \geq \frac{RA_r}{p_r^W} \quad \perp \quad p_r^W \tag{17}$$

14. Emissions (applies to emissions-regulating regions only):

$$\overline{CO_2} \geq \sum_r y_r^{ED} \quad \perp \quad p^{CO_2} \tag{18}$$

Constraints:

15. Emissions (applies to emissions-regulating regions only):

$$\overline{CO_{2r}} CO_{2r} \geq y_r^{ED} \quad \perp \quad CO_{2r} \tag{19}$$

16. CDM incentive compatibility:

$$\begin{aligned}&\left(\theta_E (p_E)^{1-\sigma} + \left(1-\theta_E\left(p_K^{\vartheta} p_L^{1-\vartheta}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}\right.\\ &\geq \frac{1}{1+\mu}\left(\theta_E (p_E(1+\tau))^{1-\sigma} + \left(1-\theta_E\left(p_K^{\vartheta} p_L^{1-\vartheta}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}\right.\\ &\perp \quad \mu_r\end{aligned} \tag{20}$$

17. CDM budget balance:

$$\mu_r p_r^Y y_r - \tau_r p^E y_r^{ED} \geq w_r \sum_s T_{sr} \quad \perp \quad \tau_r \tag{21}$$

Income balance:

$$\begin{aligned}RA_r = \overline{Q_r} q_r + \overline{K_r} v_r + \overline{L_r} w_r + p^{CO_2} \overline{CO_{2r}} CO_{2r} + w_r \sum_s T_{sr}\\ - \sum_s w_s T_{rs} + \tau_r y_r^{ED} p_r^{ED} - \mu_r y_r p_r^y \quad \perp \quad RA_r\end{aligned} \tag{22}$$

Table A1. Activity variables	
y_r	Aggregate production in region r
y_r^E	Energy supply in region r
y_r^{ED}	Energy demand in region r
y_r^A	Armington aggregate in region r
y_r^W	Welfare in region r

Table A2. Price variables	
p_r^Y	Price of aggregate output in region r
p^E	Price of energy
p_r^{ED}	Price of energy demand in region r
w_r	Wage rate in region r
v_r	Return to capital in region r
q_r	Rent to natural resources in region r
p_r^A	Price of Armington good in region r
p_r^W	Welfare price
p^{CO_2}	Price of emissions permits

Table A3. Additional variables	
CO_{2r}	CO_2 emissions in regions r
RA_r	Income level of representative agent in region r
μ_r	CDM incentive subsidy
τ_r	CDM emissions tax
T_{sr}	Value of CDM purchases

Table A4. Cost shares	
θ_r^E	Benchmark cost share of energy in aggregate output in region r
θ_r^K	Benchmark share of capital in value-added composite in region r
θ_r^R	Benchmark share of specific resource in energy production in region r
θ_{sr}^Y	Benchmark share of output from region s in consumption composite of region r
θ_r^{LW}	Benchmark share of leisure in welfare composite in region r

Table A5. Endowments	
$\overline{L_r}$	Labor endowment in region r
$\overline{ls_r}$	Benchmark leisure demand in region r
$\overline{l_r}$	Benchmark labor demand in region r
$\overline{K_r}$	Capital endowment in region r
$\overline{f_r}$	Benchmark capital demand in the energy nest in region r
$\overline{k_r}$	Benchmark capital demand in the output nest in region r
$\overline{Q_r}$	Resource endowment in region r
$\overline{CO_2}$	Emissions target
$\overline{c_{rs}}$	Benchmark bilateral trade flows
$\overline{ed_r}$	Benchmark energy demand in region r

Table A6. Elasticities	
σ	Substitution between energy inputs and the capital-labor composite
η	Substitution between capital and resources in the energy nest
γ	Substitution between the import aggregate and the domestic input

Appendix B. GAMS code of stylized CGE model

```
$title  Illustrative CGE Model of Incentive-Compatible CDM at the Sector Level

set     r       Regions /oecd,china,row/;

alias (r,rr);

parameter       c0(r,rr)        Consumption (=trade matrix),
                ls0(r)          Leisure demand,
                le0(r)          Labor + leisure endowment,
                ke0(r)          Capital endowment,
                r0(r)           Resource endowment,
                y0(r)           Output,
                l0(r)           Labor demand,
                k0(r)           Capital demand,
                f0(r)           Capital demand,
                es0(r)          Energy supply,
                ed0(r)          Energy demand,


                evs(r)          Energy value share,
                kvs(r)          Capital value share,
                sigma           Cross-price elasticity of energy demand /0.5/,
                eta             Cross-price elasticity of energy supply /0.5/,
                gamma           Cross-price elasticity in consumption demand /4/,

                cdmv(r,rr)      Value of CDM purchases,
                elim(r)         Emissions limit,
                target          Emissions target /0/;



table   bmkdata(*,r)    Stylized benchmark data
                oecd    china   row
        y0      100     40      50
        evs     0.05    0.08    0.12
        kvs     0.40    0.50    0.40
        zeta    1.75    1.25    1.25
        es0     0.4     0.1     0.5
        dvs     0.8     0.9     0.6;


evs(r) = bmkdata("evs",r);
y0(r)  = bmkdata("y0",r);
ed0(r) = evs(r)*y0(r);
es0(r) = bmkdata("es0",r)*sum(rr,ed0(rr));

f0(r)  = 0.5*es0(r);
r0(r)  = 0.5*es0(r);
kvs(r) = bmkdata("kvs",r);
k0(r)  =  kvs(r) * (y0(r)-ed0(r));
ke0(r) = f0(r) + k0(r);
l0(r)  = y0(r)-ed0(r)-k0(r);
ls0(r) = 0.5 * l0(r);
le0(r) = l0(r) + ls0(r);
cdmv(r,rr) = 0;

c0(r,r) = bmkdata("dvs",r)*(le0(r)-ls0(r)+ke0(r)+r0(r));

parameter       mchk;
mchk(r,"d0") = c0(r,r);
mchk(r,"m0") = le0(r)-ls0(r)+ke0(r)+r0(r) - c0(r,r);
mchk(r,"x0") = y0(r)-c0(r,r);
mchk("total","d0") = sum(r,c0(r,r));
mchk("total","m0") = sum(r, mchk(r,"m0"));
mchk("total","x0") = sum(r, mchk(r,"x0"));
```

```
display mchk;

*       Impose consistent bilateral trade flows (consumption):
c0(r,rr) = c0(r,rr) + mchk(r,"x0")/mchk("total","x0") * mchk(rr,"m0");

parameter mktchk;
mktchk(r,"y0") = y0(r);
mktchk(r,"d0") = c0(r,r);
mktchk(r,"x0") = sum(rr,c0(r,rr)) - c0(r,r);
mktchk(r,"y0-d0-x0") = y0(r) - sum(rr, c0(r,rr)) + eps;
display mktchk;

*       Emissions have a 1:1 relationship with energy use. Initially there is no
emission constraint:
elim(r) = 0;


*-----------------------------------------------------------------------------------
*       Algebraic model formulation in mixed complementarity format (based on
*       calibrated share form)

*       Value shares for calibrated share form:
parameter       theta_e_y(r)    Benchmark cost share of energy in macro production,
                theta_k_kl(r)   Benchmark cost share of capital in value-added,
                theta_r_e(r)    Benchmark cost share of specific resource in energy
                                 production,
                theta_l_w(r)    Benchmark cost share of leisure in welfare
                                 composite
                theta_y_a(rr,r) Benchmark cost share of output from region rr in
                                 consumption composite of region r;

theta_e_y(r)    = ed0(r)/(ed0(r)+k0(r)+l0(r));
theta_k_kl(r)   = k0(r)/(k0(r)+l0(r));
theta_r_e(r)    = r0(r)/(f0(r)+r0(r));
theta_l_w(r)    = ls0(r)/(ls0(r) + sum(rr,c0(rr,r)));
theta_y_a(rr,r) = c0(rr,r)/sum(rr.local, c0(rr,r));


positive variables
*       Activity levels:
        Y(r)    Macro output,
        A(r)    Armington production,
        E(r)    Energy supply,
        ED(r)   Energy demand,
        W(r)    Welfare,

*       Prices:
        P(r)    Macro output price,
        PA(r)   Armington price index,
        PW(r)   Welfare price index,
        PE      International energy supply price,
        PED(r)  Energy demand price,
        PL(r)   Wage rate,
        RK(r)   Return to capital,
        PR(r)   Resource price,
        PQ      Emission quota price,

*       Income level:
        RA(r)   Representative agent,

*       Additonal variables:
        EMIT(r) Emissions target,
        MU(r)   CDM incentive subsidy,
        TAU(r)  CDM emission tax;


equations
*       Zero-profit conditions:
```

```
        ZPRF_Y(r)       Zero profit for macro output,
        ZPRF_A(r)       Zero profit for Armington composite,
        ZPRF_E(r)       Zero profit for energy supply,
        ZPRF_ED(r)      Zero profit for energy demand,
        ZPRF_W(r)       Zero profit for welfare,

*       Market-clearance conditions:
        MKT_P(r)        Supply-demand balance for macro output,
        MKT_PA(r)       Supply-demand balance for Armington composite,
        MKT_PE          Supply-demand balance for energy,
        MKT_PED(r)      Supply-demand balance for energy demand,
        MKT_PL(r)       Supply-demand balance for labor,
        MKT_RK(r)       Supply-demand balance for capital,
        MKT_PR(r)       Supply-demand balance for resources,
        MKT_PQ          Supply-demand balance for emissions quotas,
        MKT_PW(r)       Supply-demand balance for welfare composite,

*       Income constraint:
        I_RA(r)         Income balance,

        EQ_EMIT(r)      Emissions balance,
        EQ_MU(r)        Constraint for endogenous CDM output subsidy,
        EQ_TAU(r)       Constraint for endogenous CDM energy tax;


*        Zero-profit conditions: c(x) >= p(x)  are complementary with activity
*         levels _|_  x

ZPRF_Y(r)..     (theta_e_y(r)*(PED(r)*(1+TAU(r)))**(1-sigma) + (1-
                    theta_e_y(r))*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                    theta_k_kl(r)))**(1-sigma))**(1/(1-sigma))
                        =e= P(r)*(1+MU(r));

ZPRF_E(r)..     (theta_r_e(r)*RK(r)**(1-eta) + (1-theta_r_e(r))*PR(r)**(1-
                    eta))**(1/(1-eta)) =e= PE;

ZPRF_ED(r)..    PE + PQ$elim(r) =e= PED(r);

ZPRF_A(r)..     sum(rr, theta_y_a(rr,r)*P(rr)**(1-gamma))**(1/(1-gamma)) =e= PA(r);

ZPRF_W(r)..     PL(r)**theta_l_w(r)*PA(r)**(1-theta_l_w(r)) =e= PW(r);

*        Market-clearance conditions s(p) >= d(p) are complementary with
*         prices _|_  p

MKT_P(r)..      y0(r)*Y(r) =e=  sum(rr, (c0(r,rr) * A(rr)) * (PA(rr)/P(r))**gamma);

MKT_PE..        sum(r, es0(r) * E(r)) =e= sum(r, ed0(r) * ED(r));

MKT_PED(r)..    ed0(r)*ED(r) =e=  ed0(r) * Y(r) * (
                    (P(r)*(1+MU(r)))/((1+TAU(r))*PED(r)) )**sigma ;

MKT_PL(r)..     le0(r) =e= ls0(r) * W(r) * PW(r)/PL(r)
                + l0(r) * Y(r)*((P(r)*(1+MU(R))/(RK(r)**theta_k_kl(r)*PL(r)**(1-
                theta_k_kl(r))))**sigma)*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                theta_k_kl(r)))/PL(r);

MKT_RK(r)..     ke0(r) =e= f0(r) * E(r) * (PE/RK(r))**eta
                + k0(r) * Y(r)*((P(r)*(1+MU(R))/(RK(r)**theta_k_kl(r)*PL(r)**(1-
                theta_k_kl(r))))**sigma)*(RK(r)**theta_k_kl(r)*PL(r)**(1-
                theta_k_kl(r)))/RK(r);

MKT_PR(r)..     r0(r) =e= r0(r) * E(r) * (PE/PR(r))**eta;

MKT_PA(r)..     sum(rr,c0(rr,r))*A(r) =e= (sum(rr,c0(rr,r)))*W(r)*PW(r)/PA(r);

MKT_PW(r)..     W(r)*(sum(rr,c0(rr,r)) + ls0(r)) =E= RA(r)/PW(r);
```

```
MKT_PQ$card(elim)..       target =e= sum(rr, ED(rr)*ed0(rr));

*        Income-balance equation:

I_RA(r)..    RA(r) =e=    r0(r)*PR(r) + ke0(r)*RK(r) + le0(r)*PL(r)
                        + PQ*elim(r)*EMIT(r)
                        + PL(r)*(sum(rr,cdmv(rr,r)))
                        - sum(rr, PL(rr)*cdmv(r,rr))
                        + TAU(r) * ed0(r) * ED(r) * PED(r)
                        - MU(r) * y0(r) * Y(r) * P(r);

*        Constraints:

EQ_EMIT(r)$EMIT.UP(r)..   elim(r)*EMIT(r) =G= ed0(r)$elim(r) * ED(r);

EQ_MU(r)..       (evs(r)*PE**(1-sigma) + (1-evs(r))*(RK(r)**kvs(r)*PL(r)**(1-
                 kvs(r)))**(1-sigma))**(1/(1-sigma)) =e=
                 (evs(r)*(PED(r)*(1+TAU(r)))**(1-sigma) + (1-
                 evs(r))*(RK(r)**kvs(r)*PL(r)**(1-kvs(r)))**(1-sigma))**(1/(1-
                 sigma)) /(1+MU(r));

EQ_TAU(r)..      MU(r)*y0(r)*P(r)*Y(r) - TAU(r)*ed0(r)*ED(r)*PE =e=
                     PL(r)*sum(rr,cdmv(rr,r));


*        MCP model definition (complementarity between equilibrium conditions and
decision variables):

model cdm_mcp /  ZPRF_Y.Y, ZPRF_E.E, ZPRF_ED.ED, ZPRF_W.W, ZPRF_A.A,
                 MKT_P.P, MKT_PE.PE, MKT_PED.PED, MKT_PL.PL, MKT_RK.RK, MKT_PR.PR,
                 MKT_PQ.PQ, MKT_PW.PW, MKT_PA.PA,
                 I_RA.RA,
                 EQ_EMIT.EMIT, EQ_MU.MU, EQ_TAU.TAU /;

*        Benchmark replication with MCP version:

*       Assign initial level values:
Y.l(r) = 1; A.l(r) = 1; E.l(r) = 1; ED.l(r) = 1; W.l(r) = 1;
P.l(r) = 1; PA.l(r) = 1; PW.l(r) = 1; PE.l = 1; PED.l(r) = 1;
PL.l(r) = 1; RK.l(r) = 1; PR.l(r) = 1;


*       No active climate policy in the benchmark equilibrium:
TAU.FX(r)  = 0;
MU.FX(r)   = 0;
EMIT.FX(r) = 0;
PQ.l       = 0;

*       Initial income level:
RA.l(r) = r0(r)*PR.l(r) + ke0(r)*RK.l(r) + le0(r)*PL.l(r) + PQ.l*elim(r)*EMIT.l(r)
          + PL.l(r)*(sum(rr,cdmv(rr,r)))- sum(rr, PL.l(rr)*cdmv(r,rr))
          + TAU.l(r) * ed0(r) * ED.l(r) * PED.l(r)
          - MU.l(r) * y0(r) * Y.l(r) * P.l(r);

cdm_mcp.iterlim = 0;
solve cdm_mcp using mcp;

*       Relax MCP iteration limit for subsequent policy counterfactuals:
cdm_mcp.iterlim = 10000;

*       Fix a numeraire for easing the MCP numerical solution:
pw.fx("OECD") = 1;


*       Illustrative unilateral climate policy constraint: We impose a 20% emission
reduction from BMK for OECD.
target          = sum(r,ed0(r)) - 0.2*ed0("oecd");
```

```
EMIT.UP("oecd") = +inf;
elim("oecd")    = 0.8*ed0("oecd");

solve cdm_mcp using mcp;

*       Now contemplate cooperation through CDM flexibility:
set     cdmlvl Alternative levels of monetary CDM transfers  /0*40/;

parameter       welfare         Welfare Impact
                taxrate         Implicit tax rate;

welfare("0",r) = 100 * (W.L(r)-1);

TAU.UP("china") = +inf;
MU.UP("china")  = +inf;
MU.LO("china")  = -inf;

taxrate("0","oecd") = PQ.L/PE.L * 100;
loop(cdmlvl$cdmlvl.val,

*       Compute CDM transfers from OECD to China as a fraction of BMK labor income
*        in China
        cdmv("oecd","china") = 0.01*(cdmlvl.val/10)*ls0("china");

*       MCP model solution
        solve cdm_mcp using mcp;
        abort$round(cdm_mcp.objval,5) "CDM model does not solve.";

        welfare(cdmlvl,r)           = 100 * (W.L(r)-1);
        taxrate(cdmlvl,"oecd")      = PQ.L/PE.L * 100;
        taxrate(cdmlvl,r)$TAU.UP(r) = TAU.L(r) * 100;

);


display welfare, taxrate;


*       Plot results using public domain gnuplot package (which must be downloaded
*        and installed before)
*       See: www.mpsge.org

set     labels(cdmlvl) /0 0, 10 1, 20 2, 30 3, 40 4 /;

$setglobal gp_opt0 "set xlabel 'CDM transfer level -- % CDM host labor earnings'"
$setglobal gp_opt1 "set ylabel 'Welfare Cost -- % EV'"
$setglobal domain cdmlvl
$setglobal labels labels
$libinclude plot welfare

$setglobal gp_opt0 "set xlabel 'CDM transfer level -- % CDM host labor earnings'"
$setglobal gp_opt1 "set ylabel 'Implicit emission tax rate -- %'"
$libinclude plot taxrate
```

Figures and tables

Table 1. Summary of CDM specific results for the reference (*REF*) scenario and for the integrated emissions-trading (*IET*) and incentive-compatible (*ICC*) representations of the CDM.

Parameter	Unit	*REF*	*IET*	*ICC*
CO_2 price in AN1	(USD/tCO_2)	36,3	14,5	15,3
CER price from NA1	(USD/tCO_2)	0,0	14,5	10,4
CDM transfers	(billion USD)	0,0	17,6	11,5
CDM offsets	(GtCO_2)	0,0	1,2	1,1
ΔEmissions(AN1)	(%)	-20,0	-9,5	-10,3
ΔEmissions(NA1)	(%)	4,0	-9,1	-8,1
ΔEmissions(Total)	(%)	-9,3	-9,3	-9,3

Table 2. Sensitivity analysis in terms of relative percentage changes in welfare in terms of equivalent variation of income (EV) and electricity output (Y(ele)) between the *IET* and *ICC* scenarios.

Scenarios modifications	ΔEV(*IET*)-ΔEV(*ICC*)		ΔY(ele,*IET*)-ΔY(ele, *ICC*)	
	AN1	NA1	AN1	NA1
main	-0,006	0,142	0,631	-9,071
esub_ff : 2	0,000	0,139	0,788	-9,486
esub_ff x 2	-0,011	0,142	0,489	-8,608
esub_arm : 2	-0,033	0,297	0,870	-8,795
esub_arm x 2	0,012	0,056	0,640	-9,254

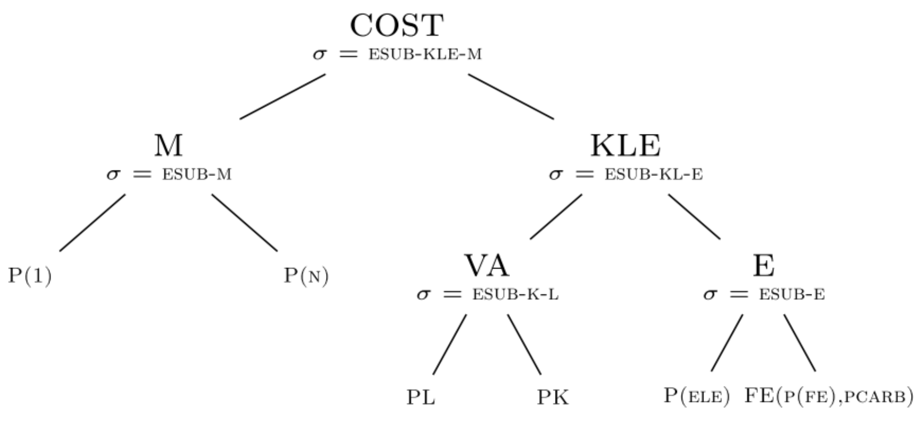

Figure 1. Nesting structure of CES cost functions (except for fossil fuels).

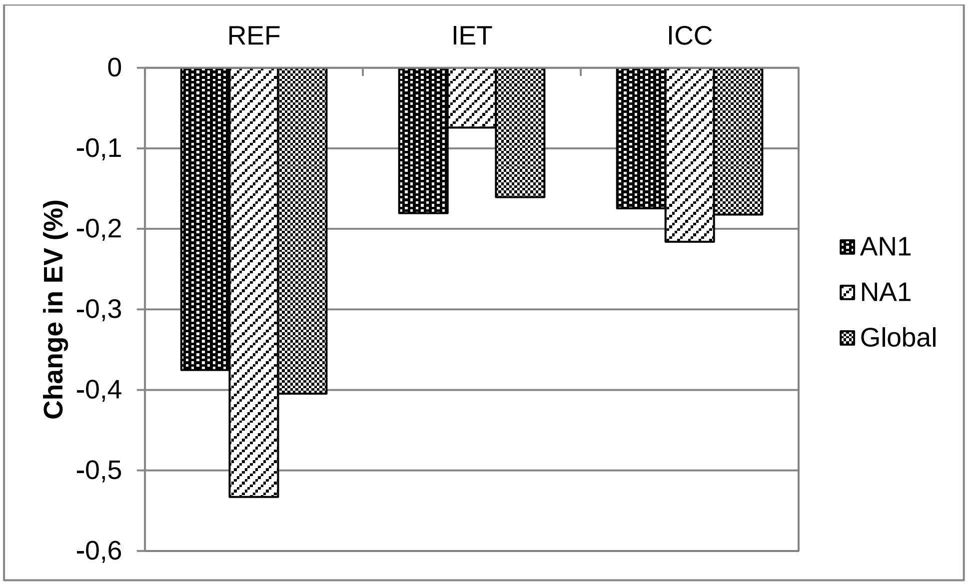

Figure 2. Changes in Hicksian equivalent variation of income (EV) in Annex I (AN1) and non-Annex I (NA1) countries, as well as globally, for the reference (*REF*) scenario and for the integrated emissions-trading (*IET*) and incentive-compatible (*ICC*) representations of the CDM.

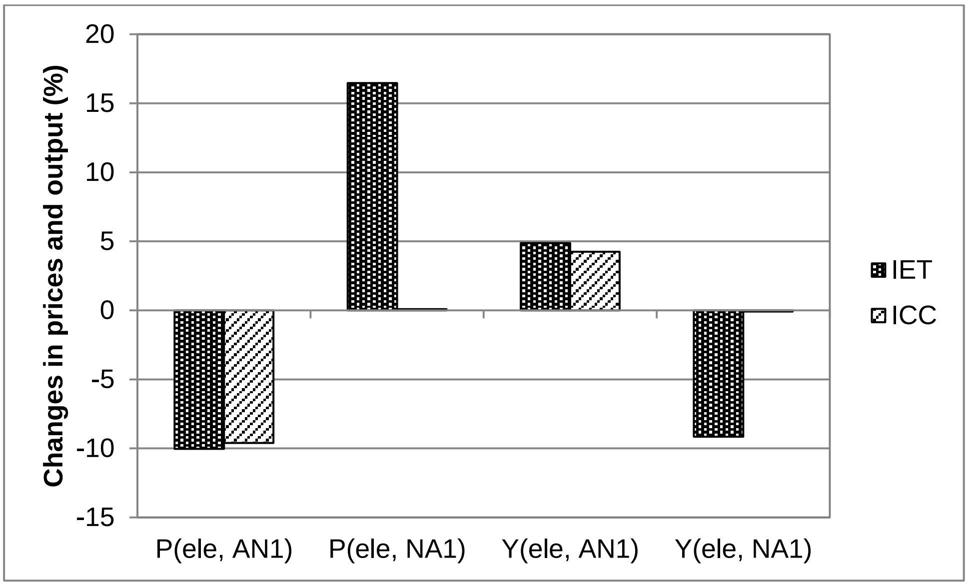

Figure 3. Changes in electricity output (Y(ele)) and electricity prices (P(ele)) in Annex I (AN1) and non-Annex I (NA1) countries for the integrated emissions-trading (*IET*) and incentive-compatible (*ICC*) representations of the CDM relative to the *REF* scenario.

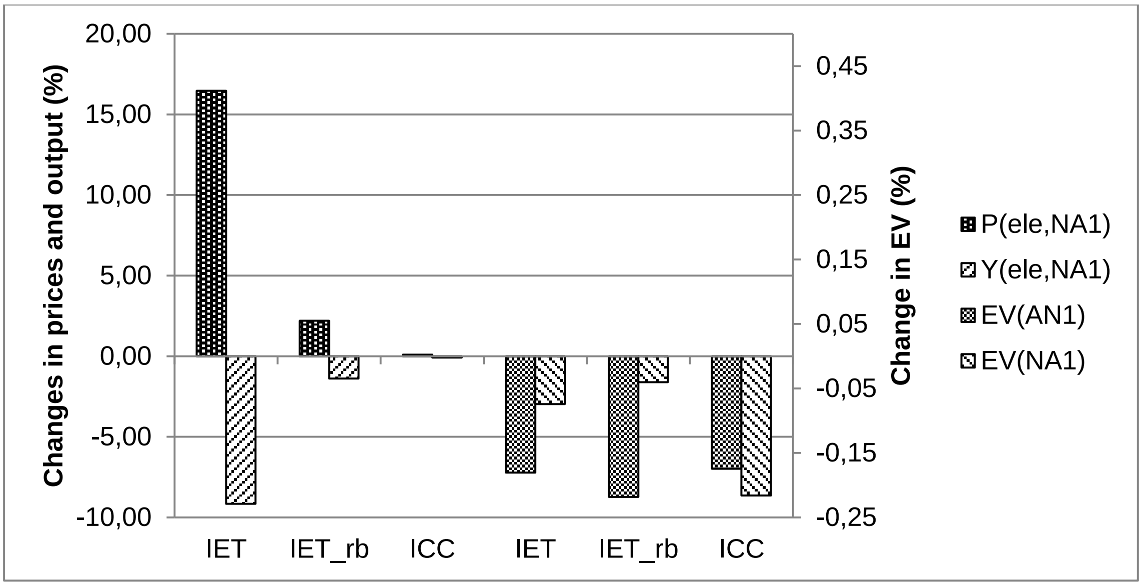

Figure 4. Comparison of sector-level impacts in prices and output (left axis) and welfare effects (right axis) across three different CDM modelling approaches: integrated emissions trading without rebates (*IET*), integrated emissions trading with rebates (*IET_rb*), and incentive-compatible CDM (*ICC*); the basis for comparison is the *REF* scenario.

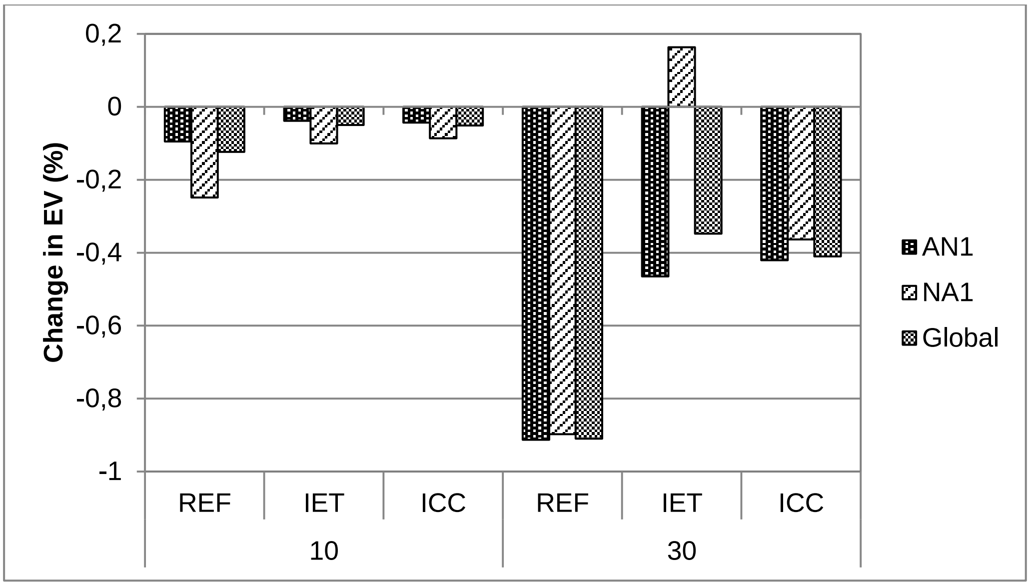

Figure 5. Changes in Hicksian equivalent variation of income (EV) in Annex I (AN1) and non-Annex I (NA1) countries, as well as globally, for the reference (*REF*) scenario and for the integrated emissions-trading (*IET*) and incentive-compatible (*ICC*) representations of the CDM under emissions-reduction targets in Annex I countries of 10% and 30%.

Zuletzt erschienen /previous publications:

V-303-08 **Heinz Welsch, Jan Kühling**, Pro-Environmental Behavior and Rational Consumer Choice: Evidence from Surveys of Life Satisfaction

V-304-08 **Christoph Böhringer and Knut Einar Rosendahl**, Strategic Partitioning of Emissions Allowances Under the EU Emission Trading Scheme

V-305-08 **Niels Anger, Christoph Böhringer and Ulrich Oberndorfer**, Public Interest vs. Interest Groups: Allowance Allocation in the EU Emissions Trading Scheme

V-306-08 **Niels Anger, Christoph Böhringer and Andreas Lange**, The Political Economy of Environmental Tax Differentiation: Theory and Empirical Evidence

V-307-08 **Jan Kühling and Tobias Menz**, Population Aging and Air Pollution: The Case of Sulfur Dioxide

V-308-08 **Tobias Menz, Heinz Welsch**, Population Aging and Environmental Preferences in OECD: The Case of Air Pollution

V-309-08 **Tobias Menz, Heinz Welsch**, Life Cycle and Cohort Effects in the Valuation of Air Pollution: Evidence from Subjective Well-Being Data

V-310-08 **Udo Ebert**, The relationship between individual and household welfare measures of WTP and WTA

V-311-08 **Udo Ebert**, Weakly decomposable inequality measures

V-312-08 **Udo Ebert**, Taking empirical studies seriously: The principle of concentration and the measurement of welfare and inequality

V-313-09 **Heinz Welsch**, Implications of Happiness Research for Environmental Economics

V-314-09 **Heinz Welsch, Jan Kühling**, Determinants of Pro-Environmental Consumption: The Role of Reference Groups and Routine Behavior

V-315-09 **Christoph Böhringer and Knut Einar Rosendahl**, Green Serves the Dirtiest: On the Interaction between Black and Green Quotas

V-316-09 **Christoph Böhringer, Andreas Lange, and Thomas P. Rutherford**, Beggar-thy-neighbour versus global environmental concerns: an investigation of alternative motives for environmental tax differentiation

V-317-09 **Udo Ebert,** Household willingness to pay and income pooling: A comment

V-318-09 **Udo Ebert,** Equity-regarding poverty measures: differences in needs and the role of equivalence scales

V-319-09 **Udo Ebert and Heinz Welsch**, Optimal response functions in global pollution problems can be upward-sloping: Accounting for adaptation

V-320-10 **Edwin van der Werf,** Unilateral climate policy, asymmetric backstop adoption, and carbon leakage in a two-region Hotelling model

V-321-10 **Jürgen Bitzer, Ingo Geishecker, and Philipp J.H. Schröder,** Returns to Open Source Software Engagement: An Empirical Test of the Signaling Hypothesis

V-322-10 **Heinz Welsch, Jan Kühling**, Is Pro-Environmental Consumption Utility-Maximizing? Evidence from Subjective Well-Being Data

V-323-10 **Heinz Welsch und Jan Kühling**, Nutzenmaxima, Routinen und Referenzpersonen beim nachhaltigen Konsum

V-324-10 **Udo Ebert**, Inequality reducing taxation reconsidered

V-325-10 **Udo Ebert**, The decomposition of inequality reconsidered: Weakly decomposable measures

V-326-10 **Christoph Böhringer and Knut Einar Rosendahl**, Greening Electricity More Than Necessary: On the Excess Cost of Overlapping Regulation in EU Climate Policy

V-327-10 **Udo Ebert and Patrick Moyes**, Talents, Preferences and Inequality of Well-Being

V-328-10 **Klaus Eisenack**, The inefficiency of private adaptation to pollution in the presence of endogeneous market structure

V-329-10 **Heinz Welsch**, Stabilität, Wachstum und Well-Being: Wer sind die Champions der Makroökonomie?

V-330-11 **Heinz Welsch and Jan Kühling**, How Has the Crisis of 2008-2009 Affected Subjective Well-Being?

V-331-11 **Udo Ebert**, The redistribution of income when needs differ

V-332-11 **Udo Ebert and Heinz Welsch**, Adaptation and Mitigation in Global Pollution Problems: Economic Impacts of Productivity, Sensitivity, and Adaptive Capacity

V-333-11 **Udo Ebert and Patrick Moyes**, Inequality of Well-Being and Isoelastic Equivalence Scales
V-334-11 **Klaus Eisenack**, Adaptation financing as part of a global climate agreement: is the adaptation levy appropriate?
V-335-11 **Christoph Böhringer and Andreas Keller**, Energy Security: An Impact Assessment of the EU Climate and Energy Package
V-336-11 **Carsten Helm and Franz Wirl**, International Environmental Agreements: Incentive Contracts with Multilateral Externalities
V-337-11 **Christoph Böhringer, Bouwe Dijkstra, and Knut Einar Rosendahl**, Sectoral and Regional Expansion of Emissions Trading
V-338-11 **Christoph Böhringer and Victoria Alexeeva-Talebi**, Unilateral climate policy and competitiveness: The implications of differential emission pricing
V-339-11 **Christoph Böhringer, Carolyn Fischer, and Knut Einar Rosendahl**, Cost-Effective Unilateral Climate Policy Design: Size Matters
V-340-11 **Christoph Böhringer, Jared C. Carbone, Thomas F. Rutherford**, Embodied Carbon Tariffs
V-341-11 **Carsten Helm and Stefan Pichler**, Climate Policy with Technology Transfers and Permit Trading
V-342-11 **Heinz Welsch and Jan Kühling**, Comparative Economic Performance and Institutional Change in OECD Countries: Evidence from Subjective Well-Being Data
V-343-11 **Heinz Welsch and Jan Kühling**, Anti-Inflation Policy Benefits the Poor: Evidence from Subjective Well-Being Data
V-344-12 **Klaus Eisenack und Leonhard Kähler**, Unilateral emission reductions can lead to Pareto improvements when adaptation to damages is possible
V-345-12 **Christoph Böhringer, Brita Bye, Taran Fæhn, Knut Einar Rosendahl** Alternative Designs for Tariffs on Embodied Carbon: A Global Cost-Effectiveness Analysis
V-346-12 **Christoph Böhringer, Jared C. Carbone, Thomas F. Rutherford**, Efficiency and Equity Implications of Alternative Instruments to Reduce Carbon Leakage
V-347-12 **Christoph Böhringer, Andreas Lange, Thomas F. Rutherford,** Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives
V-348-12 **Carsten Helm, Dominique Demougin,** Incentive Contracts and Efficient Unemployment Benefits in a Globalized World
V-349-12 **Heinz Welsch,** Organic Food and Human Health: Instrumental Variables Evidence
V-350-12 **Heinz Welsch, Jan Kühling**, Competitive Altruism and Endogenous Reference Group Selection in Private Provision of Environmental Public Goods
V-351-13 **Jürgen Bitzer, Erkan Gören**, Measuring Capital Services by Energy Use: An Empirical Comparative Study
V-352-13 **Erkan Gören,** Economic Effects of Domestic and Neighbouring Countries’Cultural Diversity
V-353-13 **Erkan Gören,** How Ethnic Diversity affects Economic Development?
V-354-13 **Christoph Böhringer, Thomas F. Rutherford, Marco Springmann;** Clean-Development Investments:An Incentive-Compatible CGE Modelling Framework