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Marginal abatement cost curves in general equilibrium: The influence of world energy prices

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Abstract

Marginal abatement cost curves (MACCs) are a favorite instrument to analyze international emissions trading. This paper focuses on the question of how to define MACCs in a general equilibrium context where the global abatement level influences energy prices and in turn national MACCs. We discuss the mechanisms theoretically and then use the CGE model DART for quantitative simulations. The result is, that changes in energy prices resulting from different global abatement levels do indeed affect national MACCs. Also, we compare different possibilities of defining MACCs—of which some are robust against changes in energy prices while others vary considerably.
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1. Introduction

In the last years marginal abatement cost curves (MACCs) have become a standard tool to analyze the impacts of the Kyoto Protocol and emissions trading. Once such curves are available for the different world regions it is very easy to determine permit prices, total abatement cost and regional emissions for different scenarios of international emissions

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trading. A detailed description of the use of the MACCs is provided in the papers of Ellerman and Decaux (1998) and Criqui et al. (1999). A number of other authors have followed the approach (Blanchard et al., 2002; den Elzen and de Moor, 2002; Löschel and Zhang, 2002; Lucas et al., 2002; van Steenberghe, 2002) analyzing scenarios such as emissions trading with and without the participation of the USA, the use of market power by Russia and the Ukraine, multiple gas abatement and banking.

All these studies implicitly assume that each region/country has its unique marginal abatement cost curve independent of, e.g. the abatement levels of other regions or whether emissions trading is taking place or not. One justification for this assumption is the finding of Ellerman and Decaux (1998) that MACCs are indeed robust with respect to such policy parameters. This is somehow a surprise as Ellerman and Decaux note themselves that with international trade the abatement level in one country influences trade flows such that the MACCs may change in other countries. Their simulations with the EPPA model though, show that the variation in prices is less than 10% between different scenarios for any given level of abatement.

Commonly, the marginal abatement cost for a certain abatement level is derived as the shadow price for the associated emission constraint. As we will discuss, this shadow price is influenced by world energy prices which differ across different abatement scenarios. The reason behind this is that abatement levels in one country influence its energy demand, which might in turn influence the world energy price. With, for example, higher world energy prices regions automatically demand less energy and emit less carbon so that the same emission target becomes less binding. The magnitude of the difference in shadow prices depends on a number of factors such as trade elasticities and trade structures. This suggests that MACCs depend on world energy prices and may shift across different abatement scenarios.

Against this background, this paper tries to clarify what MACCs are, what factors influence the MACCs in different scenarios and how the MACCs should be used. In addition, the problem of choosing the reference point for the MACC is discussed. We will first explore the energy price effects theoretically in a stylized model and second quantify them using the computable general equilibrium model DART. The main result is that not only theoretically MACCs change with varying energy prices, but that the difference can reach a magnitude that cannot be neglected.

The paper proceeds as follows. The next sections defines marginal abatement cost curves, explains how they are constructed and used in practice and presents estimates for different regions. Section 3 shows in different settings how shadow prices depend on energy prices and how this affects MACCs. Section 4 introduces the computable general equilibrium model DART, defines our scenarios and presents the results of the simulations. Section 5 concludes.

2. Marginal abatement cost curves

The idea of a marginal abatement cost curve (MACC) comes from firm or plant level models of reducing emissions. In production theory the interpretation is straightforward. Given that some activities in the production process lead to emissions of undesired substances and given some abatement technology, the marginal abatement costs represent either the marginal loss in profits from avoiding the last unit of emissions or the marginal cost of achieving a certain emission target given some level of output. Whereas the latter focuses on abatement technologies such as filters for air or water pollutants, the former concept is more interested in the overall adjustment of a firm to an emission constraint including adjustments in the level of output (McKitrick, 1999).

The concept of a MACC has been adopted recently for climate policy analyses in the context of a general equilibrium framework. It is argued that an economy as a whole can be treated like a production plant, and hence the concept of a MACC can be applied analogously. Intuitively then, a MACC for an economy represents the social cost of the last unit of emissions abated in the economy.

As most empirical studies using economy wide MACCs are concerned with CO_2 abatement a number of problems disappear. For CO_2, economical capture or sequestration technologies currently do not exist. Therefore, the question of abatement activities can be ignored and the notion of a MACC in terms of abatement cost at a given output level makes little sense in this case. CO_2 abatement is possible only through a reduction in the use of fossil fuels combined with adjustments in other inputs and a reduction in output. In addition, CO_2 emissions occur in fixed proportions to the burning of the different fossil fuels. This makes a firm level MACC for CO_2 almost trivial and the interpretation of an economy wide MACC somewhat easier.

In practice, MACCs are constructed and used without further reflecting the theoretical concepts. Two general types of models are used to analyze climate policies as well as to generate MACCs for different regions. The first approach is denoted top-down and is based on aggregated microeconomic models. The models are most often computable general equilibrium (CGE) models that may carry a detailed representation of the energy sector. Bottom-up models on the other hand are based on an engineering approach that analyses the different technical potentials for emission reductions in detail.

In a CGE model, the marginal abatement cost is defined as the shadow cost that is produced by a constraint on carbon emissions for a given region and a given time. This shadow cost is equal to the tax that would have to be levied on the emissions to achieve the targeted level or the price of an emission permit in the case of emissions trading. The more severe the constraint, the higher the marginal abatement costs are. Marginal abatement costs curves are obtained, when the costs associated with different levels of reductions are generated. Ellerman and Decaux (1998) use the EPPA model and run it with proportional reductions by all OECD countries of 1, 5, 10, 15, 20, 30 and 40% of 2010 emissions and fit simple analytical curves to the sets of plots. They find that each region has a unique curve independently of how the other regions behave and independent of how the reductions are implemented (emissions trading versus regional constraints).

Besides the EPPA-MACCs many models (Böhringer and Löschel, 2003; Blanchard et al., 2002; Criqui et al., 1999; Löschel and Zhang, 2002) use curves generated from the energy systems model POLES (Criqui et al., 1996) which is mainly a bottom-up model. Here, the MACCs are constructed the other way around. Different levels of a “shadow carbon tax” are levied on all areas of fossil fuel use. Via technological or implicit behavioral changes and the replacements in the energy conversion systems for which the technologies are explicitly defined in POLES, this leads to adjustments in the final energy demand and to the corresponding levels of emission reductions.

Another rather ad hoc approach to estimate MACCs is used by Ghersi (2001). He uses the shadow costs for the two scenarios where Kyoto is first implemented through unilateral emission reductions and second by international emissions trading which are reported for 12 different models affiliated to the Energy Modelling Forum (Weyant, 1999). This approach is only valid though, if the MACCs are indeed robust against changes of policy.

Taken together, the literature shows that the MACCs vary considerably across different models and depend on the different model types and model assumptions, e.g. on baseline growth and baseline emissions. Nevertheless, all models more or less produce the same ranking of marginal abatement costs across economies.

In the literature there are two ways to visualize MACCs: either with absolute emission reductions on the abscissa or with percentage reductions relative to the benchmark in a certain year (usually 2010). Fig. 1 shows the marginal abatement cost curves for Annex B regions of the DART model, when each country unilaterally undertakes an emission reduction in both graphical visualizations. For a comparison we also include some curves from the EPPA and the POLES model[1] taken from Criqui et al. (1999) and Ellerman and Decaux (1998). Although the curves differ across models, they result in the same ranking. The same amount of emission reductions is cheapest in the USA, followed by Eastern Europe and the Former Soviet Union (FEB) and Western Europe (WEU). The reductions are most expensive in Japan (JPN) and the remaining Annex B countries (ANC = Canada, Australia, New Zealand). Regarding relative targets, the same percentage reduction relative to the benchmark is more equal across the regions but differs more across models. To keep the figure clear, we only included the EPPA curves for WEU and the USA. Abatement is again most expensive in Japan, followed now by Western Europe and the USA, ANC and finally FEB.

It is clear that MACCs are influenced by factors such as the initial level of energy prices, the energy supply structure and the potential for developing carbon free energy resources (Criqui et al., 1999). Also, den Elzen and Both (2002) note that it is well possible that MACCs are dependent of the behavior of the rest of the world. Nevertheless, these issues have not been explored yet. We will discuss in the next section for different settings, how MACCs depend on world fossil fuel prices and how they have to be defined in a general equilibrium context.

3. The role of fossil fuel prices

Although the first intuition for regional MACCs, discussed in the last section, sounds convincing, there exist a number of traps if one tries to define in exact terms the idea of a MACC for an economy. The main aspect differentiating firm level MACCs from economy wide MACCs is the treatment of prices. At firm level output and input prices are exogenously given. Hence, the marginal abatement costs of meeting a certain emission

[1] The curves from the EPPA and the POLES model are only approximated from graphs and not generated using the exact data. Also, the regional aggregation is not exactly the same across models.

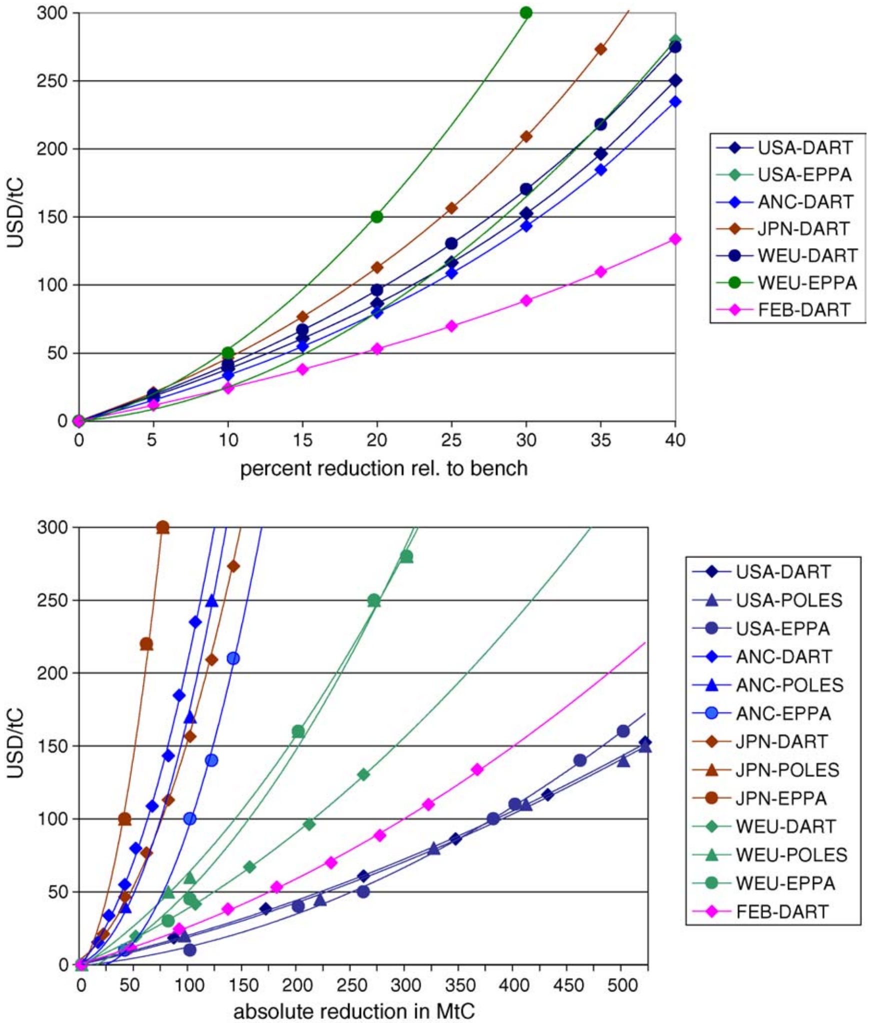

Fig. 1. Typical marginal abatement cost curves.

target consist of a combination of output reduction and end-of-pipe emission reductions, all evaluated at given prices. In a general equilibrium framework though, many prices are determined endogenously. One could in analogue to the firm level approach evaluate the MACC at constant prices. This would constitute an appropriate approach as long as only marginal costs in the neighborhood of the original equilibrium are evaluated. For the marginal cost of larger emission reductions it is likely that goods and factor prices will change. As social costs are clearly determined by the variable prices, taking the definition of the MACC seriously implies to work with variable prices.

As mentioned, MACCs are linked to shadow costs of emission constraints. These are thus the starting point for our theoretical analysis. In order to highlight issues that need to be taken into account when MACCs for an economy are to be derived we start with the firm level and then extend the approach to a whole economy. In a final step, we discuss the implications for MACCs derived from the shadow costs based on different approaches.

3.1. Emission constraints at firm level

Suppose, there is a firm that uses capital K, labor L, and fossil fuels F as inputs in the production of its output X. Input prices are exogenously given by r, w, and p_F. The price of X is without loss of generality set to 1. The technology is given by a production function G with positive but decreasing marginal products for all inputs. CO_2 emissions e depend on the amount of fossil fuel used in production, i.e. $e = \iota F$, where ι denotes the emission coefficient for F. With this simple emission function, constraining e is equivalent to restricting the input F. The profit maximization problem of the firm is

$$\max_{(K,L,F)} \pi(X) = G(K,L,F) - rK - wL - p_F F - \lambda(e - \iota F) \tag{1}$$

The first order conditions are:

$$G_K = \frac{\partial G(K,L,F)}{\partial K} = r \tag{2}$$

$$G_L = \frac{\partial G(K,L,F)}{\partial L} = w \tag{3}$$

$$G_F = \frac{\partial G(K,L,F)}{\partial F} = p_F + \lambda\iota \tag{4}$$

$$\iota F = e \tag{5}$$

With $F^* = e/\iota$ given by Eq. (5), the optimal $K^*(w, r, p_F, e)$and $L^*(w, r, p_F, e)$ are determined by Eqs. (2) and (3). By definition, $\lambda$is the shadow price of the emission constraint which is determined by Eq. (6):

$$\lambda(w, r, p_F, e) = \frac{1}{\iota} G_F\left(K^*, L^*, \frac{e}{\iota}\right) - \frac{p_F}{\iota} = \frac{1}{\iota}[G_F - p_F] \tag{6}$$

As $\frac{\partial G}{\partial e} = G_e = \frac{1}{\iota} G_F$ is the value of the marginal product of e to the firm, $\lambda + \frac{1}{\iota} p_F$ is thus nothing but the "social" costs of the emission constraint. For an unconstrained emission level e_0 the social cost would be the same as the private cost, which is $\frac{1}{\iota} p_F$ and $\lambda(e_0) = 0$. Note also that as G_F is decreasing in F, $\frac{\partial \lambda}{\partial e} = \frac{1}{\iota^2} \frac{\partial^2 G(K^*, L^*, \frac{e}{\iota})}{\partial^2 F} < 0$ and λ increases with a stricter target $e' < e$. Whether the curve of different shadow costs $\lambda(e)$ is convex, which is mostly assumed, depends on the properties of G. $\lambda(e)$ is strictly convex if and only if $\frac{\partial^3 G(K^*, L^*, \frac{e}{\iota})}{\partial^3 F} > 0$.

3.2. Emission constraints in a small open economy

Using the same approach we can also model emission constraints in a general equilibrium context of a small open economy that faces fixed world prices. The economy is now endowed with fixed amounts $\bar{K}$ and $\bar{L}$ of the two factors capital and labor which are internationally immobile and have market returns r and w. In addition, there is an intermediate input[2] F (fossil fuel) that is used in the production of the final good X. The use of F is again associated with emissions of ιF. Both goods are produced with a constant returns to scale technology. Again, X uses K, L and F and we denote the production function by G. F only uses K and L and the production function for F is

$$F = H(K, L) \tag{7}$$

Both G and H are increasing, concave and linearly homogeneous. We choose X as a numeraire with price one and assume that the world market price of F is p_F. The equilibrium is determined by the zero-profit conditions for both sectors X and F, the full employment conditions for factors K and L and market clearing for the domestic use of F and the consumption of good X. Introducing an emission constraint, leads to a shadow cost of emissions in the profit maximization of X which we again denote λ. As it is more convenient to use cost functions, we work directly with the gross price of F which is $p := p_F + \iota\lambda$. Also, we need to differentiate between the total production of F and the domestic use F_D. If we define F_I as fossil fuel imports (resp. exports if negative), then $F_D = F + F_I$. The unit cost functions are now defined as:

$$c^F(w, r) = \min_{(K,L)} (rK + wL : H(K, L) = 1) \tag{8}$$

$$c^X(w, r, p) = \min_{(K,L,F_D)} (rK + wL + pF_D) : G(K, L, F_D) = 1 \tag{9}$$

The following six equations then define the equilibrium. The first two are the free entry or zero profit conditions that result from the constant return to scale technologies. The next three are the full employment respectively market clearing conditions for the factors and the intermediate good. The last equation is the constraint on e.

$$c^F(w, r) = p_F \tag{10}$$

$$c^X(w, r, p) = 1 \tag{11}$$

$$\frac{\partial c^F(w, r)}{\partial w}(F_D - F_I) + \frac{\partial c^X(w, r, p)}{\partial w} X = \bar{L} \tag{12}$$

$$\frac{\partial c^F(w, r)}{\partial r}(F_D - F_I) + \frac{\partial c^X(w, r, p)}{\partial r} X = \bar{K} \tag{13}$$

$$\frac{\partial c^X(w, r, p)}{\partial p} X = F_D \tag{14}$$

$$\iota F_D = e \tag{15}$$

[2] F is now treated as an intermediate input, as we can think of fossil fuels as being extracted from a resource stock by using capital and labor. CGE models usually use this approach as does DART.

The exogenous parameters are the factor endowments $\bar{K}$ and $\bar{L}$, the world market price p_F for F and the emission level e which directly determines $F_D = e/\iota$. Besides F_D, the endogenous variables are X, F_I, w, r and λ. The first two equations can be solved for equilibrium factor prices w^* and r^* as a function of the exogenous parameter p_F and of λ^*. With factor prices then determined the next two equations together with $F_D = e/\iota$ solve for X^* and F^* as a function of $p_F, \bar{K}, \bar{L}, e$ and of λ^*. λ^* is determined by the fifth equation and depends on $p_F, \bar{K}, \bar{L}, e$ and p_F. Adding an income equation would deliver us the amount of X that is consumed domestically.

While on firm level an exogenous change of p_F to $p_F - \Delta$ leads to a change of λ to $\lambda + \Delta/\iota$ so that the gross price of fossil fuel under an emission constraint remains the same, the case is now more difficult. In the appendix we show that

$$\mathrm{d}\lambda = -\frac{\mathrm{d}p_F}{\iota}(1 + C(e, p_F)) \tag{16}$$

C is a constant that depends on the level of the emission target e. The first term $\frac{\mathrm{d}p_F}{\iota}$ captures the effects that were already present at firm level: to keep the demand for F in the X sector constant, the change in p_F is accompanied by the same change in λ scaled by the emission factor. But now, a decrease (or increase) in p_F does not only change the input price of F in the X sector, but also the world market price of X in relation to the price of F, which represents the terms of trade. For non-nested production functions it is possible to show that $C(e, p_F) > 0$.[3] Note also, that the change in λ captures two effects: the fall in input prices in the X sector and a shift of production between the two sectors which corresponds to the decrease in output in the firm level example.

There are other analogies to the firm level case. It is possible to show (Copeland and Taylor, 2003; Woodland, 1982) that the system of equations (10)–(15) is equivalent to maximizing the national income function where the underlying technology T is described by the production functions G and H and the emission constraint:

$$\mathrm{GDP}(\bar{K}, \bar{L}, p_F, e) = \max_{(X,F)} (X + p_F F : (X, F) \in T(X, F, e)) \tag{17}$$

A useful property of the GDP function is that the returns to capital and labor are obtained by differentiating with respect to the relevant factor endowment.

$$\frac{\partial \mathrm{GDP}(\bar{K}, \bar{L}, p_F, e)}{\partial K} = r \frac{\partial \mathrm{GDP}(\bar{K}, \bar{L}, p_F, e)}{\partial L} = w \tag{18}$$

Equivalently we have,

$$\frac{\partial \mathrm{GDP}(\bar{K}, \bar{L}, p_F, e/\iota)}{\partial F} = p_F + \iota\lambda \Leftrightarrow \lambda = \frac{1}{\iota}\frac{\partial \mathrm{GDP}(K, L, p_F, e/\iota)}{\partial F} - \frac{1}{\iota} p_F \tag{19}$$

[3] This is shown in Appendix 5. For general (including nested) production functions we were unable to determine the sign of $C(e, p_F)$. As $C(e, p_F)$ captures the terms of trade effect, the intuition suggests that always $C(e, p_F) > 0$: with a decrease in p_F the economy will tend to produce more X and less F, increasing the demand for F_D in the X sector. This in turn will increase λ even further.

and the GDP function analogous to the production or output function in the firm level case. This relationship can also be used to determine the marginal change in GDP due to a marginal change in the emission target:

$$\frac{\partial \mathrm{GDP}(\bar{K}, \bar{L}, p_F, e/\iota)}{\partial e} = \frac{1}{\iota}\frac{\partial \mathrm{GDP}(\bar{K}, \bar{L}, p_F, e/\iota)}{\partial F} = \frac{p_F}{\iota} + \lambda \tag{20}$$

If e_0 are unconstrained emissions, the total loss in GDP of reducing emissions to e^* is

$$\mathrm{dGDP} = \int_{e^*}^{e_0} \left(\lambda(e) + \frac{p_F}{\iota}\right) \mathrm{d}e = \int_{e^*}^{e_0} \lambda(e)\,\mathrm{d}e + (e_0 - e^*)\frac{p_F}{\iota} \tag{21}$$

Thus, the area under the MACC is only one part of the total loss in GDP.

3.3. Emission constraints in a large open economy

The next step would be to skip the assumption of exogenous world market prices and to assume a large open economy. As the algebra of an appropriate model becomes very tedious while the basic effects remain the same, we will only give the intuition of the differences to the small economy case.

A corresponding scenario for an exogenous shock on p_F would be the introduction of a stricter environmental policy abroad which reduces the foreign demand for F and in turn drives down p_F. As the relative price of X increases, the domestic country shifts factors from the F to the X sector and increases the output of X. At the same time, as F becomes cheaper, the X sector will use more F and less labor and capital. These two effects, which are the same as in the case of the small open economy and which are reflected in Eq. (16), will increase the domestic demand for F. To keep emissions and thus F on a constant level λ has to rise. The only difference to the small economy case is now that with less F and more X being produced domestically, the price of X decreases relative to the price of F, which implies that p_F rises. Part of the external decrease in p_F is offset by the domestic shift of production which decreases λ. Thus, in a large open economy an external shock on p_F also affects λ but this effect is less severe than in a small open economy because of an adaptation of the terms of trade.

Summarized, it is thus not p_F that influences the domestic shadow cost but the emission constraint within the economy e and the emission constraints in the rest of the world e^* that determine p_F. The influence of different emission constraints in the rest of the world on the shadow cost of the domestic economy can now be described by

$$\frac{\mathrm{d}\lambda(e, e^*)}{\mathrm{d}e^*} = -\frac{1}{\iota}(1 + D(e, e^*))\frac{\mathrm{d}p_F}{\mathrm{d}e^*} \tag{22}$$

3.4. An interpretation of MACCs

So far, we have avoided the term MACC in this theoretical part and only talked about shadow costs of emission constraints. We will now discuss how these can be used to derive MACCs under changing fossil fuel prices. Again, we start at the firm level, where the implications of different definitions can be illustrated using a social cost curve.

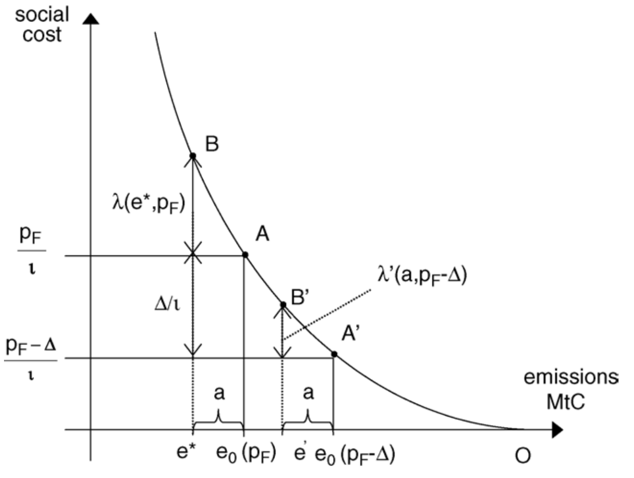

Fig. 2. The social cost curve.

At firm level all prices are exogenous. The relationship between the price of fossil fuels p_F and the shadow costs of an emission constraint, $\lambda(e)$ is

$$\frac{\mathrm{d}\lambda(e)}{\mathrm{d}p_F} = -\frac{1}{\iota} \quad \text{or} \quad \mathrm{d}\lambda(e) = -\frac{1}{\iota}\mathrm{d}p_F \tag{23}$$

This implies that for given factor and output prices, $\lambda(e) + \frac{1}{\iota} p_F$, the social costs of constraining energy use and emissions at e is simply the sum of the fossil fuel price divided by the emission coefficient for CO_2 and the shadow price of the constraint. For the cases of a small and a large open economy the relation between p_F and $\lambda(e)$ is not linear anymore. Nevertheless, as Eqs. (16) and (22) show they are still closely linked. Fig. 2 shows a typical social cost function.

The graph of the social cost is composed of the market price of fossil fuel measured in emission units and the shadow price of the emission constraint. Now take the case given in Eq. (23). If no emission constraint is imposed this curve simply depicts the unconstrained emission levels at alternative fossil fuel prices. For example, at some fossil fuel price $p_F/\iota$the emissions would be $e_0(p_F)$; similarly for $(p_F - \Delta)/\iota$ they would be $e_0(p_F - \Delta)$. If an emission target of e^* is imposed (as it is the case in the Kyoto Protocol) the social cost is – irrespectively of the prevailing price of fossil fuels – represented by point B on the social cost curve. For p_F/ι, $\lambda(e^*, p_F)$ is the part of the social cost that represents the shadow cost of the emission constraint. For $(p_F - \Delta)/\iota$ this part increases by Δ/ι. Hence, marginal abatement costs depend to a large degree on the underlying fossil fuel price.

There are now two ways in which the traditional MACCs can be derived from this social cost function. The first way consists of showing the MACC in terms of units of emissions abated, i.e. the difference between unconstrained emissions and the constrained emissions (Fig. 3 a). The MACCs, as usually drawn, would have A as the origin and take the mirror image of the graph of AB in Fig. 2. This graph would be defined for a specific price p_F.

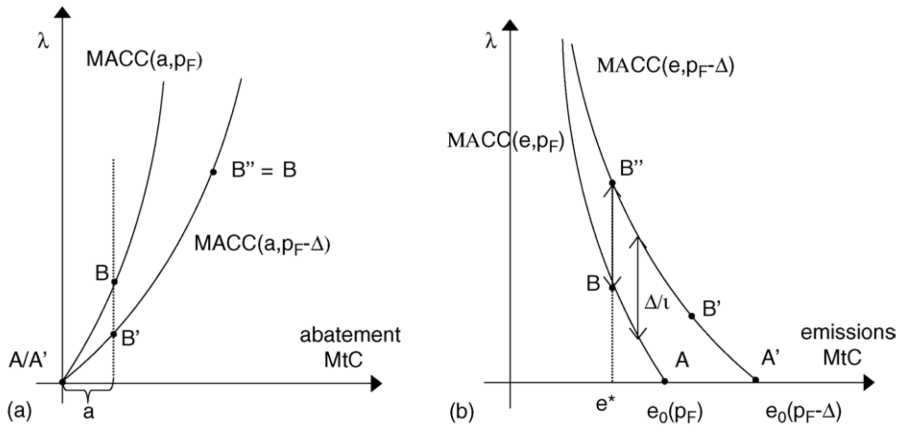

Fig. 3. Two ways of depicting MACCs.

In the case of a different reference situation (e.g. due to other policies outside the economy under consideration which result in different fossil fuel prices) such as $p_F - \Delta$ the new graph would be A'B'. The two graphs are illustrated in Fig. 3 a. In such a representation of MACCs all curves go through the origin but they have different shapes depending on the fossil fuel price at the reference point of no emission control. Fig. 3 a also shows that the same abatement effort a has different marginal abatement costs depending on the initial fossil fuel price and, therefore, different initial emissions levels.[4]

The second variant of the graph of a MACC is the representation in emission levels as shown in Fig. 3 b. In this case the abscissa of the social cost representation is kept. However, the graphs of AB and A'B' are shifted downward by the fossil fuel price at the reference situation. Hence, this MACC represents the shadow price of an emission level, i.e. net of the fossil fuel price. A certain abatement effort $a := e_0(p_F) - e^* = e_0(p_F - \Delta) - e'$ would either have marginal costs depicted by B (for an initial p_F) or by B' (for an initial $p_F - \Delta$).

In analog to the first variant of a MACC it is also possible to define a third variant with relative (instead of absolute) abatement on the abscissa. As this simply implies a re-scaling respectively a monotonic transformation of the MACCs in Fig. 3 a, the qualitative results remain the same for such MACCs.

Finally, Fig. 2 can be used to illustrate the loss in output (corresponding to a loss in GDP in a small open economy). The area $e_0(p_F)AO$ represents the cost of fossil fuels, measured in units of emissions. The additional loss due to the emission target is the area $e^*BAe_0(p_F)$. It equals the area under the MACC(e, p_F) which is e^*BA in Fig. 3 b plus the abated emissions $a = e^* - e_0(p_F)$ multiplied by p_F/ι.

For the purpose of illustrating the impact of the reference situation for deriving the MACC, consider the Kyoto commitment of a relatively small country like Japan. One could derive the MACC by assuming that the rest of the world does not impose any

[4] Note that B'' equals B on the social cost curve in Fig. 2.

emission constraint and Japan increases its abatement by the quantity a. The MACCs in Fig. 3 a and b would be represented by the graph AB. Alternatively, one could start with the AXB countries meeting the Kyoto targets and derive the Japan MACC from that reference situation. This reference situation would consist of a lower fossil fuel price $p_F - \Delta$ and result in a graph like A'B' in both Fig. 3 a and b. The quantity of emissions abated and the corresponding cost of the Kyoto Protocol would be B on the upper graph of Fig. 3 a in the first case and B on the lower graph of the same figure in the second case; i.e., in the AXB reference situation more abatement quantities and higher prices are required than in the unilateral reference situation. In the alternative representation of Fig. 3 b the emission target of the Kyoto Protocol is $e^*$and the corresponding MACCs would either be represented by AB (the left graph) or by A'B'B'' (the graph on the right). In this case the higher baseline emissions due to the negative demand effect on fossil fuels of the AXB countries meeting their Kyoto targets becomes apparent through higher baseline emissions $e_0(p_F - \Delta)$.

The question of robustness of MACCs can now be addressed either by looking at the difference in costs for a certain abatement a such as B and B' in Fig. 3 a. Or one could ask for the robustness of the marginal cost estimate for meeting a certain cap such as e^*. In this case the difference of the points B and B'' on the two graphs of both Fig. 3 a and b is assessed.

When moving to a general equilibrium setting in a small open economy, the resource constraint on capital and labor needs to be accounted for. The economy now faces an economy wide emissions constraint, a given factor endowment, and exogenous world market prices. As shown in Eq. (16) changes in p_F and changes in shadow prices λ are in this case not linearly independent due to the term $C(e, p_F)$. As a result, the social cost of a certain emission constraint depends on p_F and there is – different to the firm level case – not one single social cost curve but one curve for each p_F. This is shown in Fig. 4. Here, the

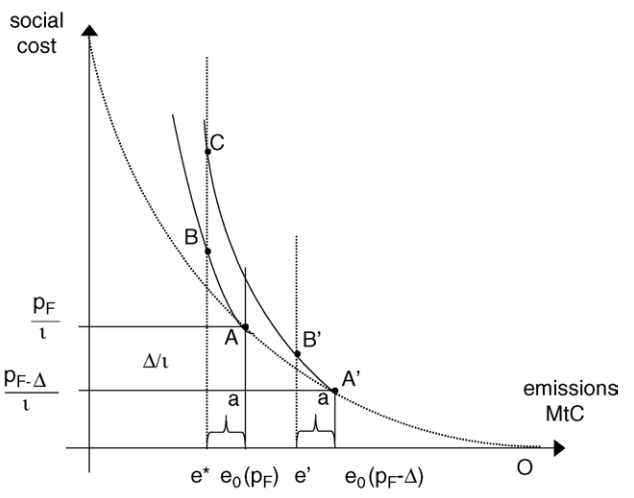

Fig. 4. Social cost curves in a small open economy.

dotted curve represents the unconstrained emissions that are associated with different p_F. If emissions are now constraint at some given $p_F$the social cost curve for that p_F starts at A. For a different $p_F - \Delta$ it starts at A'. The MACCs corresponding to the MACCs for the firm level in Fig. 3 a, are the curves going again through AB and A'B'. The MACCs corresponding to the curves in Fig. 3 b are now AB and A'B'C.

The most complex case is the one of a large open economy where world market prices become endogenous. Thinking, e.g., of a two country model, the only exogenous parameters are now the factor endowments and policies. With respect to climate policy, it is not p_F that influences the domestic social costs of a certain emission constraint e and any derived MACC but the emission constraints in the rest of the world $\bar{e}$. Together, e and $\bar{e}$ then determine p_F. The mechanisms through which the economies interact in the world economy become quite complex now. A set of emission constraints $(e, \bar{e})$ can be used to derive first a particular social cost curve. This curve now results – for a given $\bar{e}$ and for varying levels of e – in variable fossil fuel prices p_F since these prices are not only determined by $\bar{e}$ (as in the small country case) but also by e itself. Hence, fossil fuel prices vary along a particular social cost curve. This makes the derivation of the part that is not inherent in the fossil fuel price (the MAC) more complex and implies that fossil fuel prices vary along any derived MACC as well. Again the question is as to whether this endogeneity really shows up in empirically derived curves.

If it does, it has consequences for using MACCs. Take an example with two economies, "home" with target e and "foreign" with target $\bar{e}$. Suppose the $\text{MACC}_\text{h}(e, \bar{e})$ for home is derived by varying e for a given $\bar{e}$ which is a straightforward exercise. The problem is, there is no corresponding $\text{MACC}_\text{f}(e, \bar{e})$ of the foreign economy as each emission constraint e will result in a different $\text{MACC}_\text{f}(e, \bar{e})$. That means to each point on $\text{MACC}_\text{h}(e, \bar{e})$ corresponds a particular $\text{MACC}_\text{f}(e, \bar{e})$ and vice versa. In that sense the exercise of using several regional MACCs for establishing shadow prices of emission constraints or for deriving trade flows in an emissions trading system must fail unless the MACCs are insensitive enough with respect to the emission level abroad.

4. Empirical results

To quantify the strength of the shifts in the MACCs in different scenarios for different regions, we use the CGE model DART.

4.1. Simulations with the DART model

The DART (**D** ynamic **A** pplied **R** egional **T** rade) model is a multi-region, multi-sector recursive dynamic CGE model of the world economy developed at the Kiel Institute for World Economics to analyze climate policies. In the version used for this paper it covers 11 sectors and 12 regions and the two production factors labor and capital. The regional aggregation for this study includes the USA, Japan (JPN), Western Europe (WEU), the Former Soviet Union and Eastern Europe (FEB), and the remaining Annex B parties (ANC: Australia, New Zealand, Canada), that agreed to emission reductions in the Kyoto

Protocol. The economic structure of the DART model is fully specified for each region and covers production, final consumption and investment. For a more detailed model description see Klepper et al. (2003).

We now use the DART model to quantify the effects of different reference scenarios on the location and shape of the MACCs. Many different reference situations can be imagined. Since the Kyoto Protocol is an often used simulation scenario we compute the MACCs for the year 2010 at which the Kyoto commitments will be binding. We choose two scenarios for which we compute the MACC:[5]

- UNI: In the UNI scenario a country reduces its emissions whereas all other countries are assumed to follow a growth path without any emission constraint.
- AXB: All Annex B countries, except the region for which the MACC is constructed, reduce emissions according to their Kyoto commitment.[6] The reductions are achieved by unilateral emission taxes. As in our model FEB does not reach its target emissions in 2010 they do not face reductions.

For these two scenarios two sets of numbers are computed. The UNI set consists of the results of a unilateral emission reduction schedule between the unconstrained emissions and a 40% reduction relative to benchmark emissions in each of the five Annex B regions mentioned above. The targets are varied in steps of 5% points. The AXB set consists of the same reductions in each region but under the assumptions that the other Annex B regions meet their Kyoto target.

These data are then used to compute the three representations of MACCs as discussed above. The results for these curves are given in Tables B.1 and B.2. Table B.1 corresponds to the MACCs shown in Fig. 3 b. Table B.2 shows the numbers for Fig. 3 a, once in terms of abated quantities and once as the percentage abated relative to the unconstrained emissions in the respective scenario.

4.2. Simulation results

The numbers in Table B.1 are based on absolute emission targets for each region and thus resemble the MACCs in Fig. 3 b. The unconstrained emission level in the scenario UNI differs from that of the scenario AXB and thus the points A and A' in Fig. 3 b represent UNI and AXB. The emission target e^*(Fig. 3 b) could be the Kyoto target marked with an ‘‘a’’ in Table B.1. The points B and B’’ would correspond to the MAC of Kyoto under UNI and AXB. It is clear that meeting the target e^*would require different abatement levels under the two reference scenarios for computing MACCs. In contrast, the point B' in

[5] We do not consider emissions trading here, as with emissions trading the abatement levels of all countries change in comparison to the unilateral action scenario and are dependent on the participants in the trading scheme. We would thus not only see a shift in MACCs, but also a move along one curve. As the focus of this paper is on the shift of the curves, we restrict ourselves to the non-trading case.

[6] The Kyoto targets applied in this study are the targets induced by the agreements in Bonn and Marrakech and include sinks. We use the reductions cited in Böhringer (2002) and derive the targets for our regional aggregation using IEA emission data. The targets are relative to 1990 emissions: USA: 96.8%, WEU: 94.8%, ANC: 109%, JPN: 99.2% and FEB: 103%.

Fig. 3 b would represent the same abatement level under AXB as under UNI. However, it would not lead to the same emission target.

Table B.2 a shows the quantities for the MACCs in terms of abatement levels as represented in Fig. 3 a. The origin of the graphs of the MACCs represents the unconstrained emission levels both in UNI and in AXB. Notice, however, that the origin of the two curves refers to different baseline emissions with AXB levels being higher than UNI levels. If we again take the Kyoto target for a particular region, e.g. Japan, that corresponds to a reduction of about 80 MtC. The point B in Fig. 3 a would then result in MACs of 116.13 USD, whereas point B' – the same abatement level under scenario AXB – would result in MACs of 104.35 USD.

Similarly shaped graphs of MACCs as in Fig. 3 a would emerge from the numbers in table 2b. The difference is in the scaling of the abscissa.[7] It should be kept in mind that drawing the MACCs in relative changes yields again different abatement levels since the baseline in UNI and AXB differs. Hence, a certain percentage reduction of x % would not represent the same absolute reduction in both scenarios.

There are now essentially three ways of defining robustness of the MACCs corresponding to the three representations. The first which is probably used by Ellerman and Decaux (1998) refers to the representation in percentage reductions and compares a certain percentage reduction of a% in the two scenarios, hence it compares B' and B in Fig. 3 a when drawn not in levels abated but in percentages abated. The second would do the same exercise in absolute abatement levels, hence comparing B and B' in Fig. 3 a. Finally, one can compare the two MACCs in terms of a certain emission target, e.g. the Kyoto target. This would result in a comparison of B and B'' which both represent the same emission target under the two scenarios.

When we compute these differences it turns out that the first approach to checking robustness would always result in deviations of less than 10% in the simulations of DART, supporting the results of Ellerman and Decaux (1998). In fact, the difference is in most countries even below 5%, and only reaches 6% resp. 7% in Japan and ANC. In the second approach with fixed absolute abatement relative to the unconstrained emissions, the difference is still below 10% in most cases and only reaches 11–13% for high abatement levels in Japan and ANC. The third variant, however, leads to substantial differences in the MACs for a given emission target, that can reach up to 50% for low abatement levels. For example, in WEU, JPN and ANC the difference between the MAC based on the UNI and one based on the AXB reference for the Kyoto target is above 20%.

In addition, corresponding to the theoretical findings, the simulation results show qualitatively different moves of the MACC UNI to the MACC AXB in the three representations. As an example, Fig. 5 depicts these three representations for Japan.

For fixed emission targets (Table B.1 and Fig. 5 c) we can see that the MACC is indeed shifted upward through lower fossil fuel prices in AXB as shown in Fig. 3 b. Since we are computing the general equilibrium effects the presentation in the simplified framework of

[7] To be precise, the move from absolute to relative targets does not only imply a re-scaling of the abscissa, but also a shift in the relative position of the two MACCs since the reference situations have different emission levels.

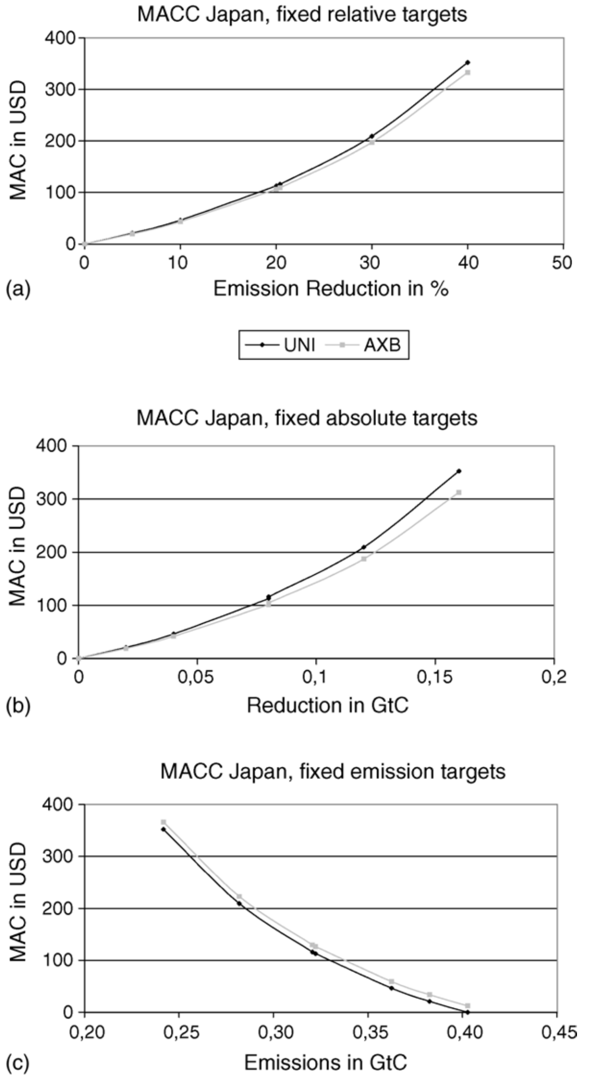

Fig. 5. The MACCs for Japan in three different representations.

the firm level MACC needs to be checked against the social cost curves as shown in Fig. 4. In fact, the numbers computed and the graphs of Fig. 5 show that the shape of the MACCs which would be determined by the adjustment in the terms-of-trade does not significantly change. Hence, the two social cost curves shown in Fig. 4 have very similar shape. This indicates that the major influence on the robustness of MACCs is induced by the fossil fuel price effect of different reference scenarios and not by the endogeneity of those prices in a general equilibrium framework. One should be aware, however, that we are computing rather small changes in relative prices based on actual policy proposals. For larger changes the general equilibrium effects may need to be taken into account when assessing the robustness of MACCs.

The strength of the shift imposed by different reference scenarios varies, depending on the region, between 2 and 14 USD/tC. It is influenced among other things by each countries share of Annex B emissions and the importance of energy exports or imports.[8] In the case of the USA, for example, the shift is much smaller (around 5 USD/tC) than for Japan (around 14 USD/tC). The parallel shift also explains, why the relative difference between the two MACCS is higher for lower abatement levels.

In the case of MACCs in terms of emissions abated (Table B.2 and Fig. 5 a and b) the move from UNI to AXB turns the MACC clockwise around the origin. Finally, the difference between UNI and AXB is from this point of view much smaller then the difference for fixed emission targets. Again, this corresponds to the graphical example where the difference between B and B' in Fig. 3 a is smaller then the difference between B and B'' in Fig. 3 b. As a result MACCs in terms of abatement levels are robust, while MACCs in terms of emission targets are not.

5. Conclusions

In the previous sections we have shown theoretically and empirically how marginal abatement cost curves depend on abatement levels in the rest of the world via changes in international fossil fuel prices. We also discussed three different possibilities to derive graphs for MACCs from the social cost curves of emission restrictions: in terms of emission targets, in terms of absolute abatement relative to the unconstrained emission level and finally in terms of relative (%) abatement relative to the unconstrained emission level. For each of these approaches one can define measures of robustness with respect to the reference situation of the simulation exercise. It turns out that even though in all cases MACCs react to energy prices, this reaction is rather small in the two latter cases, so that the MACCs in terms of absolute or relative abatement levels can be termed robust. The MACCs in terms of emission targets though, may change considerably.

The question remains whether there is one "true" representation of a MACC. We believe this is not the case, since the three representations refer to three different ways of looking at the problem. The MACCs in terms of absolute or relative abatement levels show the marginal cost of a certain reduction level starting from a particular reference situation that is not explicitly shown in such graphs. Hence, the impact of fossil fuel prices on the overall social cost is not very transparent. Such MACCs turn out to be quite robust, mainly because absolute and relative abatement levels are taken without reference to particular emission targets. However, the costs of reaching, e.g., the Kyoto target with a fixed emission level, may be better illustrated with the MACCs shown in terms of emission levels. These graphs implicitly take into account the effect of different reference situations influencing fossil fuel prices. They are less robust, mainly because for reaching a certain

[8] See Klepper and Peterson (2003) for a detailed discussion on the factors influencing the strength of the shift.

emission target the abatement levels need to be varied under different reference situations thus leading to an amplification of marginal costs.

Instead of using the MACCs one could directly refer to the social cost curve for achieving a certain emission target. This approach explicitly takes into account the interaction of marginal abatement costs and fossil fuel prices. In addition, it is the social cost curve that is used to determine the welfare loss in terms of GDP of a certain emission target—not any of the MACCs. As the social cost is the sum of the fossil fuel price and the marginal abatement cost, the information of MACs alone – not accompanied by the associated fossil fuel prices – is of little help.

The theoretical part has shown that in the setting of open economies unique social cost curves of emissions only exist for a particular fossil fuel price – in the case of a small open economy – or for a particular emission level in the rest of the world—in the case of a large open economy. They define a set of curves as illustrated in Fig. 4. For empirical purposes, however, the simulations have shown that the differences in the shapes of these curves are very small when compared to the differences imposed by the fossil fuel prices. The discussion about the robustness of MACCs is in fact concerned with the shape of different social cost curves at different segments of these curves. In contrast, the open economy effects on the social cost curve determine the distance between the social cost curves under different reference scenarios which do hardly change the shape of a MACC. In summary, the robustness of MACCs with respect to different reference situations is something to check when transferring MACCs derived from a particular simulation exercise to other policy scenarios. The international relative price effects of the open economy framework, on the other hand, do not seem to affect MACCs in a significant way.

Appendix A. Shift of the MACC in a small open economy

In this section we show how the MACC for a given emission target $\bar{e}$ shifts with a change in the exogenous price of the fossil fuel p_F. To facilitate the notation we define

$$p_F + \lambda\iota = p, \qquad \frac{\partial c^i}{\partial j} = c^i_j, \qquad \frac{\partial c^i}{\partial j \partial j'} = c^i_{jj'}, \quad i = F, X, \quad j, j' = w, r, p$$

Note that $\forall\, i, j$

$$c^i_j > 0; \qquad c^i_{jj'} > 0 \quad \text{for} \quad j \neq j' \quad \text{and} \quad c^i_{j^2} < 0 \tag{24}$$

For better readability we repeat the system of equations describing the equilibrium in the small open economy with the new notation:

$$c^F(w,r) = p_F, \qquad c^X(w,r,p) = 1, \qquad c^F_w(w,r)\left(\frac{e}{\iota} - F_I\right) + c^X_w(w,r,p)X = \bar{L},$$

$$c^F_r(w,r)\left(\frac{e}{\iota} - F_I\right) + c^X_r(w,r,p)X = \bar{K}, \qquad c^X_p(w,r,p)X = \left(\frac{e}{\iota}\right)$$

Assuming an exogenous change of $d p_F$ taking the total derivative gives

$$\underbrace{\begin{pmatrix} c_w^F & c_r^F & 0 & 0 & 0 \\ c_w^X & c_r^X & \iota c_p^X & 0 & 0 \\ a_1 & a_2 & \iota c_{wp}^X X & c_w^F & c_w^X \\ a_3 & a_4 & \iota c_{rp}^X X & c_r^F & c_r^X \\ c_{pw}^X X & c_{pr}^X X & \iota c_{p^2}^X X & 0 & c_p^X \end{pmatrix}}_{A} \underbrace{\begin{pmatrix} \mathrm{d}w \\ \mathrm{d}r \\ \mathrm{d}\lambda \\ -\mathrm{d}F_I \\ \mathrm{d}X \end{pmatrix}}_{b} = -\mathrm{d}p_F \underbrace{\begin{pmatrix} -1 \\ c_p^X \\ c_{wp}^X X \\ c_{rp}^X X \\ c_{p^2}^X X \end{pmatrix}}_{c}$$

$$a_1 = c_{w^2}^F\left(\frac{e}{\iota} - F_I\right) + c_{w^2}^X X \quad a_2 = c_{wr}^F\left(\frac{e}{\iota} - F_I\right) + c_{wr}^X X,$$

$$a_3 = c_{rw}^F\left(\frac{e}{\iota} - F_I\right) + c_{rw}^X X \quad a_4 = c_{r^2}^F\left(\frac{e}{\iota} - F_I\right) + c_{r^2}^X X$$

If A^λ is matrix A with the third column replaced by the vector c the solution for $\mathrm{d}\lambda$ is by Cramer's Rule

$$\mathrm{d}\lambda = \frac{|A^\lambda|}{|A|} \quad \text{with } |\cdot| = \det(\cdot)$$

Developing A^λ by the third row we obtain:

$$|A^\lambda| = \mathrm{d}p_F|B| - \frac{\mathrm{d}p_F}{\iota}|A|, \qquad B = \begin{pmatrix} c_w^X & c_r^X & 0 & 0 \\ a_1 & a_2 & c_w^F & c_w^X \\ a_3 & a_4 & c_r^F & c_r^X \\ c_{pw}^X X & c_{pr}^X X & 0 & c_p^X \end{pmatrix}$$

$$\mathrm{d}\lambda = -\frac{\mathrm{d}p_F}{\iota} + \mathrm{d}p_F \frac{|B|}{|A|}$$

Under some assumptions it is possible to determine the sign of $|A|$ and $|B|$.

$$\begin{aligned} |B| &= c_w^X \begin{vmatrix} a_2 & c_w^F & c_w^X \\ a_4 & c_r^F & c_r^X \\ c_{pr}^X X & 0 & c_p^X \end{vmatrix} - c_r^X \begin{vmatrix} a_1 & c_w^F & c_w^X \\ a_3 & c_r^F & c_r^X \\ c_{pw}^X X & 0 & c_p^X \end{vmatrix} \\ &= c_w^X c_{pr}^X X(c_w^F c_r^X - c_w^X c_r^F) - c_r^X c_{pw}^X X(c_w^F c_r^X - c_w^X c_r^F) + c_w^X c_p^X(a_2 c_r^F - a_4 c_w^F) \\ &\quad - c_r^X c_p^X(a_1 c_r^F - a_3 c_w^F) = X(c_w^X c_{pr}^X - c_r^X c_{pw}^X)(c_w^F c_r^X - c_w^X c_r^F) \\ &\quad + c_w^X c_p^X(a_2 c_r^F - a_4 c_w^F) - c_r^X c_p^X(a_1 c_r^F - a_3 c_w^F) \end{aligned}$$

As $c_j^i > 0$ and due to (30) a_1, $a_4 < 0$ and a_2, $a_3 > 0$ the last two terms (including the sign) are positive. For simple production functions, like, e.g. a simple Cobb–Douglas or CES function $c_{pw}^X / c_{pr}^X = c_w^X / c_r^X$ and thus $c_w^X c_{pr}^X - c_r^F c_{pw}^X = 0$ so that the first term is zero and $|B|>0$. For more complicated production functions that are, e.g. nested, the sign of the first term depends on the assumptions about the capital intensity in F and X (second bracket) and the input elasticities in the production of X (first bracket).

For A we have

$$
\begin{aligned}
|A| &= c_w^F \begin{vmatrix} c_r^X & \iota c_p^X & 0 & 0 \\ a_2 & \iota c_{wp}^X X & c_w^F & c_w^X \\ a_4 & \iota c_{rp}^X X & c_r^F & c_r^X \\ c_{pr}^x X & \iota c_{p^2}^x X & 0 & c_p^X \end{vmatrix} - c_r^F \begin{vmatrix} c_w^X & \iota c_p^X & 0 & 0 \\ a_1 & \iota c_{wp}^X X & c_w^F & c_w^X \\ a_3 & \iota c_{rp}^X X & c_r^F & c_r^X \\ c_{pw}^x X & \iota c_{p^2}^x X & 0 & c_p^X \end{vmatrix} \\
&= (c_w^F c_r^X - c_r^F c_w^X) \begin{vmatrix} \iota c_{wp}^X X & c_w^F & c_w^X \\ \iota c_{rp}^X X & c_r^F & c_r^X \\ \iota c_{p^2}^x X & 0 & c_p^X \end{vmatrix} - \iota c_w^F c_p^X \begin{vmatrix} a_2 & c_w^F & c_w^X \\ a_4 & c_r^F & c_r^X \\ c_{pr}^x X & 0 & c_p^X \end{vmatrix} \\
&\quad + \iota c_r^F c_p^X \begin{vmatrix} a_1 & c_w^F & c_w^X \\ a_3 & c_r^F & c_r^X \\ c_{pw}^x X & 0 & c_p^X \end{vmatrix} = \iota X (c_w^F c_r^X - c_r^F c_w^X)[c_{p^2}^X (c_w^F c_r^X - c_r^F c_w^X) \\
&\quad + c_p^X (c_{wp}^X c_r^F - c_{rp}^X c_w^F)] - \iota c_p^X c_w^F c_{pr}^X X (c_w^F c_r^X - c_w^X c_r^F) - \iota (c_p^X)^2 c_w^F (a_2 c_r^F - a_4 c_w^F) \\
&\quad + \iota c_p^X c_r^F c_{pw}^X X (c_w^F c_r^X - c_w^X c_r^F) + \iota (c_p^X)^2 c_r^F (a_1 c_r^F - a_3 c_w^F) \\
&= \iota [c_{p^2}^X X (c_w^F c_r^X - c_r^F c_w^X)^2 - 2 c_p^X X (c_w^F c_r^X - c_r^F c_w^X)(c_{rp}^X c_w^F - c_{wp}^X c_r^F) \\
&\quad - (c_p^X)^2 c_w^F (a_2 c_r^F - a_4 c_w^F) + (c_p^X)^2 c_r^F (a_1 c_r^F - a_3 c_w^F)]
\end{aligned}
$$

The first term is negative as $c_{p^2}^X < 0$. The third and the forth term are negative due to (30) and as $a_1, a_4 < 0$ and $a_2, a_3 > 0$. For simple Cobb–Douglas and CES functions, the second term has the same sign as

$$
-\left(\frac{c_w^F}{c_r^F} - \frac{c_w^X}{c_r^X}\right)\left(\frac{c_w^F}{c_r^F} - \frac{c_{wp}^X}{c_{rp}^X}\right) = -\left(\frac{c_w^F}{c_r^F} - \frac{c_w^X}{c_r^X}\right)^2 < 0
$$

Thus together $|A|<0$. For more complicated production functions, additional assumptions are again necessary to determine the sign of the second term.

For all constant return to scale production functions the result implies for $\mathrm{d}\lambda$ that

$$
\mathrm{d}\lambda(e, p_F) = -\frac{\mathrm{d}p_F}{\iota} - \frac{\mathrm{d}p_F}{\iota}\frac{\iota|B|}{|A|} = -\frac{\mathrm{d}p_F}{\iota}\left(1 + \frac{\iota|B|}{|A|}\right) := -\frac{\mathrm{d}p_F}{\iota}\Big(1 + C(e, p_F)\Big)
$$

For given K, L and p_F the original equilibrium values for w, r, X and F_I depend on the emission target e. Thus both B, A and also $|B|, |A|$ vary with the emission target. For Cobb–Douglas and CES functions it was shown that $C(e, p_F) > 0$.

Appendix B. Simulation results

Table B.1
Marginal abatement cost curves—I

	Emission target in GtC	MAC in USD	
		UNI	AXB
USA	1.75	X	0.00
	1.73	0.00	4.53
	1.55	38.32	42.97
	1.38[a]	85.24	90.25
	1.38	86.24	91.36
	1.21	152.58	158.28
	1.04	250.32	256.94
WEU	1.08	X	0.00
	1.05	0.00	11.07
	0.94[a]	41.15	51.88
	0.94	41.62	52.35
	0.84	96.24	106.79
	0.73	170.40	180.69
	0.63	274.98	284.85
JPN	0.42	X	0.00
	0.40	0.00	12.13
	0.36	46.43	59.28
	0.32	112.93	126.30
	0.32[a]	116.13	129.51
	0.28	209.15	222.91
	0.24	352.39	366.38
ANC	0.27	X	0.00
	0.26	0.00	11.05
	0.24	33.67	44.99
	0.23[a]	46.45	57.70
	0.21	79.66	90.79
	0.18	143.34	154.29
	0.16	234.86	245.47
FEB	0.94	X	0.00
	0.91	0.00	7.00
	0.82	24.34	30.90
	0.73	53.18	59.44
	0.64	88.59	94.76
	0.55	133.88	140.18

[a] Kyoto target.

Table B.2
Marginal abatement cost curves—IIa and IIb

	Reduction in GtC[a]	MAC in USD		Reduction in %[a]	MAC in USD	
		UNI	AXB		UNI	AXB
USA	0.00	0.00	0.00	0	0.00	0.00
	0.17	38.32	37.61	10	38.32	38.14
	0.34[b]	85.24	83.26	19.8[b]	85.24	84.62
	0.35	86.24	84.33	20	86.24	85.71
	0.51	152.58	148.25	30	152.58	151.20
	0.99	250.32	241.85	40	250.32	247.80
WEU	0.00	0.00	0.00	0	0.00	0.00
	0.10[b]	41.15	37.76	9.9[b]	41.15	39.11
	0.11	41.62	38.20	10	41.62	39.56
	0.21	96.24	87.96	20	96.24	91.59
	0.32	170.40	154.86	30	170.40	162.33
	0.42	274.98	247.93	40	274.98	262.17
JPN	0.00	0.00	0.00	0	0.00	0.00
	0.04	46.43	41.89	10	46.43	43.54
	0.08	112.93	101.50	20	112.93	106.22
	0.08[b]	116.13	104.35	20.4[b]	116.13	109.20
	0.12	209.15	186.93	0.28	209.15	197.20
	0.16	352.39	312.29	0.24	352.39	333.01
ANC	0.00	0.00	0.00	0	0.00	0.00
	0.03	33.67	29.71	10	33.67	31.15
	0.03[b]	46.45	40.94	13.1[b]	46.45	43.02
	0.05	79.66	70.03	20	79.66	73.96
	0.08	143.34	125.27	30	143.34	133.54
	0.01	234.86	203.35	40	234.86	219.38
FEB	0.00	0.00	0.00	0	0.00	0.00
	0.09	24.34	22.82	10	24.34	23.61
	0.18	53.18	49.70	20	53.18	51.60
	0.27	88.59	82.55	30	88.59	86.12
	0.36	133.88	124.29	40	133.88	130.48

[a] Reduction rel. to the unconstrained emissions that differ between UNI and AXB.
[b] Reduction that leads to Kyoto target in UNI.

References

Blanchard, O., Criqui, P., Kitous, A., 2002. After the Hague, Bonn and Marrakech: the future international market for emission permits and the issue of hot air, Institute d'Economie et de Politique de l'Energy, 2002. Cahier de Recherche, 27, Paris.

Böhringer, C., 2002. Climate politics from Kyoto to Bonn: from little to nothing. The Energy Journal 23 (2), 51–71.

Böhringer, C., Löschel, A., 2003. Market power in international emission trading: the impacts of U.S. withdrawal from the Kyoto protocol. Applied Economics 35 (6), 651–663.

Copeland, B.R., Taylor, S.M., 2003. Trade and the Environment—Theory and Evidence. Princeton University Press.

Criqui, P., Cattier, F., Menanteau, P., Quidoz, M., 1996. POLES 2.2 Reference Guide. Technical report, Institute of Energy Policy and Economics.

Criqui, P., Mima, S., Viguir, L., 1999. Marginal abatement cost of CO_2emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model. Energy Policy 27, 585–601.
den Elzen, M.G.J., Both, S., 2002. Modelling emission trading and abatement cost in FAIR1.1. RIVM report 728001/021, Netherland National Institute of Public Health and the Environment (RIVM).
den Elzen, M.G.J., de Moor, A.P.G., 2002. Evaluating the Bonn-Marrakech agreement. Climate Policy 2, 111–117.
Ellerman, D.A., Decaux, A., 1998. Analysis of Post-Kyoto CO_2 Emission Trading Using Marginal Abatement Curves. Report 40, Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change.
Ghersi, F., 2001. SAP 12. Technical Description, C.I.R.E.D.
Klepper, G., Peterson, S., 2003. On the Robustness of Marginal Abatement Cost Curves: The Influence of World Energy Prices. Kiel Working Paper 1138, Kiel Institute for World Economics.
Klepper, G., Peterson, S., Springer, K., 2003. DART97: A description of the multi-regional, multi-sectoral trade model for the analysis of climate policies. Kiel Working Paper 1149, Kiel Institute for World Economics.
Löschel, A., Zhang, Z.X., 2002. The economic and environmental implications of the US repudiation of the Kyoto protocol and the subsequent deals in Bonn and Marrakech. Weltwirtschaftliches Archiv 138, 711–746.
Lucas, P.L., den Elzen, M.G., van Vuuren, D.P., 2002. Multi-gas abatement analysis of the Marrakech Accords. Paper prepared for the conference on Global Trading; Kiel 30. September 1–October 2002.
McKitrick, R., 1999. A derivation of the marignal abatement cost curve. Journal of Environmental Economics and Management 37, 306–314.
van Steenberghe, V., 2002. CO_2 abatement costs and permit's price: exploring the impact of banking and the role of future commitment. Paper prepared for the conference on Global Trading; Kiel 30. September 1–October 2002.
Weyant, J.P. (Ed.), 1999. The cost of the Kyoto Protocol—a multi-model evaluation. The Energy Journal, Special Issue.
Woodland, A.D., 1982. International Trade and Resource Allocation. North-Holland, Amsterdam.