Schwerhoff, Gregor; Edenhofer, Ottmar

Conference Paper

Low-Carbon Development through International Specialization

Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Growth and Environment, No. C04-V1

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Schwerhoff, Gregor; Edenhofer, Ottmar (2013) : Low-Carbon Development through International Specialization, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Growth and Environment, No. C04-V1, ZBW - Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft, Kiel und Hamburg

This Version is available at:
https://hdl.handle.net/10419/80036

Low-Carbon Development through International Specialization

Gregor Schwerhoff[*], Ottmar Edenhofer[†‡]

November 2012

Abstract

A major concern in climate negotiations is that decarbonization may significantly hurt the development process. This paper shows that international specialization can contribute to making environmental and economic objectives compatible. When carbon efficiency differs between two trading partners, environmental policy affects production cost differentially, so that the comparative advantage in technology is endogenous. Under a global climate agreement, a universal carbon tax would shift the production of energy intensive goods towards carbon efficient economies. Once emissions are correctly internalized, trade becomes unambiguously beneficial for the environment and allows pursuing both environmental objectives and fast economic growth. Even in the absence of a climate agreement, free trade provides the option of indirectly accessing carbon efficient technology abroad. This improves the marginal rate of substitution between consumption and environmental quality and thus achieves emission reductions even without international cooperation.

JEL classification: F18, F64, H23, Q56

Keywords: Low-Carbon Development, Carbon Leakage, International trade

[*]Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany, email: schwerhoff@pik-potsdam.de

[†]Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany

[‡] We thank Brian Copeland, Scott Taylor and workshop participants from the ZEW Summer Workshop 2012 on "Trade and the Environment" for helpful discussions.

1 Introduction

In negotiations about reductions in CO_2 emission, emerging economies sometimes bring to bear that reducing emissions may significantly hamper their prospect of continuing or attaining a rapid process of development. In this context, we show that trade and the indirect access to advanced technology that comes along with it may allow low-carbon development. By importing the most energy intensive goods from abroad developing countries can achieve high economic growth rates with carbon intensities significantly below those of the already developed economies at the same stage of development.

International trade provides the possibility to exploit comparative advantages. Environmental policy provides an incentive to relocate production according to environmental criteria. Together, these two policies make low-carbon development much more realistic than it would be without the international cooperation that these policies require. Countries which have hardly invested in developing clean technology could benefit from the existing knowledge in other regions. In return they would provide goods where they have a comparative advantage based on a combined assessment of productive and environmental technology.

While developing countries might have previously had a competitive advantage from lax environmental standards, it would now be the carbon efficient countries which are best suited to produce energy intensive goods. The production of energy intensive goods would thus move to advanced economies, but the gains from trade would assure that less developed countries can develop quickly nevertheless. The countries producing energy efficient goods can sell to a global market and thus have enormous returns to technology investments in carbon efficiency.

In environmental economics the desire of households for consumption and a clean environment is usually conceptualized in the utility function. Government policies on the environment thus trade off consumption versus pollution. Typically there is an optimum level of pollution at which total utility is maximized. At this optimum, consumption is at a level below the level of consumption that would result from maximizing consumption without considering pollution. Taking the example of a carbon tax, a zero carbon tax would maximize consumption, while the utility maximizing level of the carbon tax is positive.

Nevertheless, the idea of sacrificing consumption (respectively growth) in order to increase utility appears to be unsettling, at least to some stakeholders. Demonstrating the possibility of low-carbon development may therefore support the case of those trying to reduce emissions

through government policy. The loss of consumption in the case of free trade is much smaller than in the inflexible case of autarky, because trade allows countries to specialize. A country with a carbon-inefficient technology in energy-intensive sectors would not loose much of its production, but could specialize on goods which are not energy intensive and buy the energy intensive good from the carbon-efficient foreign country.

The model applied may appear rather drastic on first sight: Countries would completely switch their pattern of specialization. This is not to be taken literally, however. Trade-induced specialization along the lines of carbon efficiency will also work at the margin (for the most emnergy-intensive industries) and for new production facilities, so that any additional economic activity would be done in an environmentally beneficial way, thus achieving low-carbon development.

Since it is the efficient solution, we first consider the case of a global climate agreement which sets optimal carbon taxes. Such an agreement would provide the correct price signals for carbon emissions so that firms internalize the social costs in the production of carbon intensive goods. Once the prices are right, international trade can unfold its beneficial powers. It decreases emissions and increases consumption. In fact, environmental policy and the possibility to trade with advanced economies may combine to allow emerging economies to perform at least as good as the benchmark, the advanced economies in the past, in terms of growth, while performing much better in terms of emissions.

As things stand, however, an effective global climate agreement may never come to pass. Even in this case, free trade should have beneficial effects on the environment. Consider the case of a carbon-inefficient producer of an energy-intensive good. Without trade, small improvements in reducing emissions will come at a heavy cost of lost output and consumption. Under free trade there is crucially more flexibility. The energy-intensive industry would (partially at least) relocate abroad. Small losses in output would come along with large reductions of emissions, since the foreign country is more efficient.

But why is it that carbon taxes play such a crucial role? Couldn't low-carbon development through trade occur even without taxes? From our reading of the literature on the environmental Kuznets curve, there are so far no empirical signs of the downwards sloping branch of the curve. And given that advanced economies are not yet reaching a carbon efficient phase of development there is no hope of emerging economies "jumping over" the carbon intensive phase of development. Following the theoretical literature on the EKC, we think that political

cooperation for introducing a carbon tax may constitute a threshold, which could eventually be overcome ("threshold effect"). The downward-sloping part of the EKC would then be the manifestation of an "income effect", the effect that households put increasing emphasis on a clean environment when income rise.

One part of the literature focuses on the components of comparative advantage which determine the environmental effect of trade liberalization. Models like Pethig (1976) and Chichilnisky (1994) point to differences in environmental regulation as a comparative advantage. They cause a pollution haven effect as polluting industries settle in less regulated regions and export to regulated ones. Copeland and Taylor (1994) show that this effect also appears when environmental policy is endogenous. Copeland and Taylor (2004) split the effect of trade liberalization on the environment into income, substitution and composition effect. The composition of production depends on comparative advantage in environmental policy and technology. Our contribution to this literature is to point out that the comparative advantage in technology is endogenous to environmental policy when differences in carbon efficiency are considered.

Once countries are linked through trade, strategic interaction in environmental policy has an important impact on the environmental outcome. While papers like Carraro and Siniscalco (1993) and Barrett (1994) study what it takes to build or maintain international cooperation, very few papers analyze policy interaction of trade partners in the absence of global cooperation. One of the exceptions is Copeland and Taylor (2005) which considers the reaction of one country to an increase in taxes in another country. The reaction is decomposed into the income, technique and scale effect. This paper shows how the the carbon tax response function is affected by the more favorable marginal rate of transformation in free trade. A government can deliberately shift energy-intensive production to a more carbon efficient economy in order to gain a large environmental improvement.

The observation that so far there is no empirical evidence for an EKC for CO_2 can be found in Stern (2004) and Dinda (2004) among others. The ideas of a threshold and income effect for environmental pollution are taken from Jones and Manuelli (1995) and John and Pecchenino (1994), respectively.

Section 2 describes the theoretical framework which is applied in the two following sections for two scenarios. Section 3 considers the case of a global climate agreement and describes how the two policies of environmental taxes and international trade interact to affect consumption

and pollution. Section 4 considers the effect of carbon efficiency as a comparative advantage when there is no cooperation in climate policy. Section 5 reviews the state of the literature on the environmental Kuznets curve in order to motivate the necessity of carbon taxes in the analysis of low-carbon development. Section 6 concludes.

2 The Model Framework

Galor and Mountford (2006) use a basic Ricardian model to illustrate how world regions specialize in their comparative advantage, in their case skilled and unskilled intensive goods. In this spirit, we use a Ricardian model to show how carbon efficiency can become a comparative advantage for a world region once emission externalities are internalized by firms through a carbon tax.

2.1 The Setup

Firms. There are two sector and two countries. One sector produces without pollution and is therefore labelled as "clean". The other sector is energy intensive and will therefore be marked as "dirty". The countries however vary in carbon efficiency, meaning that one country can produce a unit of output in this sector with less carbon emissions.

Output Y^c in the clean sector is

$$Y^c = A^c L^c \tag{1}$$

where A^c is the productivity and L^c is the level of employment in the clean sector. Output in the dirty sector is

$$Y^d = A^d L^d \tag{2}$$

and global emissions

$$Z = A^Z Y^d \tag{3}$$

are released for every unit of the dirty good. The dirty good producer may have to pay a carbon tax $0 \leq \tau$. A^Z is the carbon-efficiency. Prices for the clean good are normalized to 1, so that $P^c = 1$ and $P^d = P$. Markets are perfectly competitive so that firms make zero

profit:

$$A^c L^c = wL^c \,, \tag{4}$$

$$PA^d L^d = wL^d + \tau Z \,. \tag{5}$$

Households. Households cannot directly influence the level of pollution, so that they are limited to maximizing utility from consumption

$$u(C^c, C^d) = \alpha \ln(C^c) + (1-\alpha) \ln(C^d) \,. \tag{6}$$

They face the budget constraint

$$wL = C^c + PC^d \tag{7}$$

and allocate labor optimally between the two sectors, $L = L^c + L^d$.

Government. Following the standard in environmental economics, we assume utility to be derived from consumption of the two goods as well as a clean environment:

$$U(C^c, C^d, Z) = u(C^c, C^d) - h(Z + Z^*) \tag{8}$$

The disutility from emissions depend on foreign emissions, Z^*, as well since carbon emissions are a global good. The government taxes carbon emissions by imposing the carbon tax τ. We do not specify what happens with the tax revenues, since a lump-sum transfer to the households would have no effect. It would only affect the level of prices (nominal prices), whereas relative prices determine real allocations (money is neutral).

2.2 Autarky

For comparison with the effect of a carbon tax on consumption and pollution, we first analyze the case of autarky. We take the tax rate of the government as given and determine the optimal values for consumption of the two goods and pollution for the government. For distinction with free trade, variables will later be labelled with the index Z_{Aut}. As long as this distinction is clear by the context, the index is dropped.

Proposition 1 *Under autarky, consumption is*

$$\begin{aligned} C^c &= \alpha A^c L, \\ C^d &= (1-\alpha) A^d \frac{A^c}{A^c + \tau A^z A^d} L \, . \end{aligned}$$

Locally emitted pollution is $Z = A^Z (1-\alpha) A^d \frac{A^c}{A^c + \tau A^z A^d} L$ *and the relative price for consumers is* $P = A^c / A^d + \tau A^Z$.

Note that for a carbon tax of zero, the standard Ricardian result emerges for dirty good consumption, $C^d = (1-\alpha) A^d L$. The fraction of consumption in the dirty good lost due to the introduction of the carbon tax, $1 - \frac{A^c}{A^c + \tau A^z A^d}$, increases with the tax and decreases as the carbon efficiency improves (A^Z decreases).

3 Low-carbon development with a Climate Agreement

In this section, the only environmental policy that we allow is a global climate agreement. It imposes a universal carbon tax in both countries. We compare four policy scenarios which result from combining trade and environmental policies. The model is static so that gains from trade result from exploiting comparative advantages.

The case where neither free trade nor environmental policy is implemented will be considered the benchmark scenario. Free trade alone generates an allocation in which energy intensive goods are produced where carbon efficiency is not a concern, so that total emissions increase. This is the "carbon leakage" scenario. A universal carbon tax without free trade will internalize the emission externality, but leaves no room for rearranging production, leading to significant losses in output. Since this seems to be an important concern of developing countries at climate negotiations, the scenario is termed the "developing country nightmare". Finally, the combination of free trade and a universal carbon tax turns carbon efficiency into a comparative advantage, so that energy intensive production moves to carbon efficient producers. This allows high consumption at low emission levels and will thus be considered as "low-carbon development". The details of this will be explored in sections 3.1 and 3.2. An overview is provided by the following table:

	Autarky	**Free Trade**
No environmental policy	Benchmark	Carbon Leakage
Universal Carbon Tax	"Developing Country Nightmare"	Low-carbon Development

Table 1: The policy matrix of trade and environmental policy

The scenarios in the column "autarky" have already been treated in Section 2.2. The benchmark scenario is the case of $\tau = 0$.

We now consider the case where the two countries can trade freely. The goods which each country produces depend on comparative advantages in productivities in the two goods, A^c and A^d, as well as carbon efficiency, A^Z. The importance of carbon efficiency will turn out to depend on the level of the carbon tax. To illustrate this, we assume that the home country is more efficient in producing the dirty good, whereas the foreign country is efficient in producing the clean good. In addition, the foreign country is more carbon efficient. Formally, we make the following assumptions. Foreign variables will be denoted with a star.

Assumption 1. The home country has better technology in the dirty good sector, $A^d > A^{d*}$, while the foreign country has better technology both in the clean sector $A^c < A^{c*}$ and in carbon efficiency, $A^Z > A^{Z*}$.

This constellation seems to be typical for trade between developing and advanced economies. Developing economies have a comparative advantage in energy intensive goods, but they have a lower carbon efficiency. Empirical studies show this pattern for Chinese trade with Japan (Liu et al. (2010)), the US (Xu et al. (2009)) and in general (Lin and Sun (2010), Xu et al. (2011)).

We assume that the relative size of productivities is such that countries are initially fully specialized:

Assumption 2.

$$\frac{A^c}{A^d} < \frac{\alpha}{1-\alpha}\frac{A^{c*}L^*}{A^dL} < \frac{A^{c*}}{A^{d*}} \tag{9}$$

Accordingly, the dirty good is produced only in the home country and the clean good in the foreign country when there is zero carbon taxation. Note that assumption 2 follows directly from assumption 1 for $\alpha = 0.5$ and $L^* = L$.

In order to classify the specialization of the two countries we define the following thresh-

olds:

$$\tau_1 = \frac{1}{A^Z A^d}\left(\frac{\alpha}{1-\alpha}A^{c*}\frac{L^*}{L} - A^c\right) \tag{10}$$

$$\tau_2 = \frac{1}{A^Z - A^{Z*}}\left(\frac{A^{c*}}{A^{d*}} - \frac{A^c}{A^d}\right) \tag{11}$$

With the help of these thresholds we observe that the production of the dirty good is gradually moved toward the carbon efficient economy when the carbon tax rises. At first the home country starts producing the clean good in addition to the dirty good. Then, the foreign country starts producing the clean good and in the next step, the home country stops producing the dirty good and fully specializes on the clean good.

Proposition 2 *In the case of free trade and given assumptions 1 and 2, specialization in the two countries depends on the level of taxation in the following way:*

	goods produced in home country	*goods produced in foreign country*
$0 \leq \tau < \tau_1$	D	C
$\tau_1 \leq \tau < \tau_2$	D,C	C
$\tau = \tau_2$	D,C	D,C
$\tau_2 < \tau$	C	D,C

3.1 Partial Cooperation

Both a global climate agreement and international trade require international cooperation. It turns out that cooperating only on one of the dimensions creates undesirable outcomes. The case where no cooperation takes place at all will be the benchmark and is defined as no international trade and no carbon tax ($\tau = 0$).

If free international trade is implemented, consumption increases, since the countries can specialize and goods will be produced with the best technology available. But without any global climate agreement, carbon efficiency is neglected and production shifts towards producers who sacrifice clean production in favor of high output (high A^d but also high A^Z). This shift in production implies an increase in pollution. Consequently this scenario will be labelled "carbon leakage" and could be considered the "environmentalist nightmare". It is defined as free international trade and no carbon tax ($\tau = 0$).

If it is the other way around and a global climate deal is implemented in the absence of free trade, the reverse will happen. The climate deal increases the relative price for the dirty

good. This reduces pollution, but it also reduces consumption. The producer who has not invested much into carbon efficiency looses out most in terms of consumption and there is no escape through trade. This scenario is labelled the "developing country nightmare" and is defined as free trade and a high carbon tax ($\tau > \tau_2$).

In order to make the scenarios comparable, we must make assumptions on the valuation of the two goods and the relative size of the countries. A general formulation would require a number of case distinctions.

Assumption 3.

$$\alpha = 0.5, \quad L = L^* \tag{12}$$

Using this assumption we can compare the two scenarios defined in this section with the benchmark.

Proposition 3 *Let assumptions 1, 2 and 3 hold. (i) In the carbon leakage scenario consumption and pollution are higher than in the benchmark scenario. (ii) In the "developing country nightmare" scenario pollution and consumption are lower than in the benchmark scenario.*

This proposition illustrates that each one of the two scenarios described above improves upon the benchmark in one way, but makes it worse in the other way. Both effects are well understood of course, but written in this way it sets the stage for an investigation of the combination of the two effects.

3.2 Full Cooperation

The remaining scenario to be considered is free international trade and a high carbon tax ($\tau > \tau_2$). The high carbon tax gives an advantage to the economy with the more carbon efficient technology for producing the dirty good. The production technology as such and the carbon efficiency are combined to determine the comparative advantage.

The benchmark scenario could also be considered to be the situation of the now developed economies in the past. There was no environmental policy, but large scale trade with the part of the world which is developing now was not yet possible. Compared to this, the current developing economies have the opportunity to trade on a large scale with the developed world. If this is combined with a global climate agreement, they could achieve high levels of consumption at low rates of pollution compared to the developed world at a similar stage. This way they can achieve development without having to go through a carbon-intensive

phase, which is why we label the full cooperation scenario (free trade, $\tau > \tau_2$) as low-carbon development.

Proposition 2 shows that in the low-carbon development scenario, the home economy produces the clean good, while the foreign economy produces both the clean and the dirty good. Consequently, the international price equals the relative price in the foreign economy: $P^i = \frac{A^{c*}}{A^{d*}} + \tau A^{z*}$. Solving for the equilibrium using this expression yields terms that cannot be conclusively compared to the values of the other scenarios (see the proof of proposition 4 for an illustration). So in order to proceed with the comparison of scenarios, we make the following assumption:

Assumption 4.

$$A^{Z*} = 0 \tag{13}$$

Under this assumption, the foreign economy is not only more carbon efficient than the home economy, it can produce both goods without any carbon emissions at all. The assumption is extreme of course, but it illustrates the potential of low-carbon development. If the assumption is weakened, weaker versions of Propositions 4 and 5 will apply.

Proposition 4 *Let assumptions 1, 2, 3 and 4 hold. (i) In the low-carbon development scenario pollution and consumption is lower than in the carbon leakage scenario. (ii) In the low-carbon development scenario pollution is lower and consumption is higher than in the developing country nightmare scenario.*

This proposition highlights that under a global climate agreement, free trade reduces the environmental burden and increases consumption. This is intuitive, it follows from a shift of dirty good production toward the more carbon efficient economy.

Finally we can compare the low-carbon development scenario with the benchmark scenario:

Proposition 5 *Let assumptions 1, 2 and 4 hold. In the low-carbon development scenario pollution is lower than in the benchmark scenario. Consumption in the clean good as well as the dirty good in the foreign economy is equal in the two scenarios. Consumption of the dirty good in the home economy however is lower in low-carbon development.*

Note that this result does not make use of assumption 3 so that it holds for general α and $L \neq L^*$. The carbon tax is set to increase welfare and accordingly, welfare is higher

in low-carbon development than in the benchmark. Consumption however is slightly below the benchmark, even under the favourable Assumption 4. The reason is that the tax forces the two economies to produce with reversed specialization. This simple static framework is therefore not quite able to achieve low-carbon development in the sense of exceeding benchmark consumption. This may however be achieved if dynamic effects are taken into account. One such dynamic effect could be a specialization in research. If both countries develop only the technology in which they are specialized, there would be "dynamic gains from trade", which would let the low-carbon development outperform the benchmark, even when only consumption is considered.

4 Low-Carbon Development Without a Climate Agreement

In this section the carbon tax rates in the two countries, τ and τ^* can differ and each country sets its carbon tax rate individually. The government chooses only the tax rate and anticipates the optimizing behaviour of households and firms.

4.1 The Samuelson Rule

Abbreviating $C(\tau) = u(C^c(\tau), C^d(\tau))$ we can write the government objective function, which has been introduced in (8), as

$$U(C(\tau), Z(\tau) + Z^*(\tau^*)) \tag{14}$$

with $\frac{\partial U}{\partial C} = U_C > 0$, $U_Z < 0$, $C_\tau > 0$, $Z_\tau > 0$, $Z^*_{\tau^*} > 0$. An analogous function U^* is defined for the foreign economy, so that local emissions have an effect on utility in the foreign economy.

The optimality condition for the government is

$$\frac{-U_Z}{U_C} = \frac{C_\tau}{Z_\tau} \,. \tag{15}$$

This illustrates the classic problem of public good provision: The externality of carbon emissions on utility in the foreign country is neglected. If the domestic government would set its taxes so as to optimize world utility

$$U(C(\tau), Z(\tau) + Z^*(\tau^*)) + U^*(C^*(\tau^*), Z(\tau) + Z^*(\tau^*)) \tag{16}$$

the Samuelson rule would follow:

$$\frac{-U_Z - U_Z^*}{U_C} = \frac{C_\tau}{Z_\tau} \, . \tag{17}$$

4.2 Trade and the Marginal Rate of Transformation

Trade as described in Section 2 cannot eliminate the inefficiency that results from the difference between the private and the social optimum. So even if countries trade, the equilibrium tax rate from equation (15) will be inefficiently low compared to the tax rate from (17). However, the inefficient tax rate in the case of trade will be much higher than the inefficient tax rate in the case of autarky. The reason is that the marginal rate of substitution, $\frac{-U_Z}{U_C}$, is higher and the marginal rate of transformation, $\frac{C_\tau}{Z_\tau}$, is lower for any given τ. Consequently, the point of intersection will be at a much higher level of the carbon tax. In the remainder of this subsection, we will substantiate this claim.

In the case of autarky, a textbook picture of public good provision emerges. Pollution and consumption goods depend in a differential way on the carbon tax, so that we can derive explicit expressions for the marginal rate of substitution (MRS) and the marginal rate of transformation (MRT). The MRS decreases monotonically and the MRT increases monotonically (see appendix), so that we obtain a unique optimal tax rate. In the illustration in Figures 1 to 3 the case of autarky is shown in blue. In Figure 3, the bold line is the MRS for one country and the dashed line the sum of both MRS.

In the case of trade we will have to consider again "threshold tax rates" at which the specialization of countries changes as in Proposition 2. The reason for this is again that comparative advantage reverses when carbon efficiency is given increasing importance through the carbon tax. Let us take the foreign tax rate τ^* as given and consider the effect of changes in the home country tax, τ. The determination of the threshold tax rates τ_1 and $\tau_2'(\tau^*)$ is shown in the proof of Proposition 6. For values of home taxes below τ_1, the home country is specialized on the dirty good. Taxes therefore don't have an effect and $C_\tau = Z_\tau = 0$. Above τ_1, the home country shifts production to the clean good with increasing taxes, so that both pollution and consumption slowly decrease.

At the second threshold, τ_2', a change occurs. The comparative advantage of producing the dirty good passes over to the carbon efficient foreign economy. Let the index $_1$ denote production and pollution at a tax rate just below τ_2' and index $_2$ just above. Then the effect

of the reversal of comparative advantage can be summarized in the following result:

Proposition 6 *For a given foreign tax rate of τ^*, there is a threshold tax rate for the home country $\tau_2'(\tau^*)$ at which the production of the dirty good moves from the carbon inefficient to the carbon efficient economy. At this point the marginal rate of transformation makes a discrete jump downward:*

$$Z_1 - Z_2 = (A^Z - A^{Z*})C_1^d + A^{Z*}(C_1^d - C_2^d) \, .$$

The change in production, $C_1^d - C_2^d$, may be positive, since the foreign country uses a less productive technology, $A^{d*} < A^d$, or it may be negative since the better carbon efficiency implies a lower tax burden on the dirty good. The first part of the sum is unambiguously positive since the foreign country is more carbon efficient. This part implies an over-proportional decrease of pollution.

The amount of dirty good production and pollution is illustrated in red in Figures 1 and 2. One possible position of MRS and MRT is illustrated in Figure 3. Since Z_τ is zero outside of the interval $[\tau_1, \tau_2']$, the MRT is not defined there. However, if the valuation for a clean environment is large enough, then the utility maximizing tax rate will be at τ_2'. In other words, the bargain of somewhat less consumption vs. much less pollution will be worthwhile.

In the illustration in Figure 3 MRS and MRT (the bold lines in red) do not intersect. If they intersect at the interior of $[\tau_1, \tau_2']$, this intersection could be a local maximum, with a higher utility attained in τ_2' due to the discrete jump of the MRT.

4.3 Trade Liberalization and Endogenous Carbon Tax Reaction

The improved trade-off between environmental quality and consumption described in proposition 6 implies that carbon taxes will be increased when trade is liberalized. To show this, we specify function h from the definition of utility in equation (8) to be linear:

$$h(Z + Z^*) = \beta * (Z + Z^*) \, . \tag{18}$$

The utility function is therefore

$$U(C^c, C^d, Z) = \alpha \ln(C^c) + (1 - \alpha) \ln(C^d) - \beta * (Z + Z^*) \, . \tag{19}$$

The parameter β therefore indicates the preference of consumers for a clean environment. Intuitively, if β is zero, the optimal carbon taxes are zero both in autarky and under free trade. If on the other hand, if β is very large, the government is willing to sacrifice a lot of consumption in order to avoid environmental damage. The taxes will be very high in autarky and trade. But as it turns out, there is an intermediate case. For moderate values of β, home country taxes are low in autarky, because the low domestic carbon efficiency requires large consumption sacrifices to gain in environmental quality. In free trade however, the home country can set the taxes so high that production of the dirty good relocates to the foreign economy. This relocation yields such large gains in environmental quality that the home economy is willing to make the required sacrifices in consumption.

Consider first the case of autarky. Inserting the values from proposition 1 into equation (19) shows that utility in the home economy depending on home carbon taxes has an inverted-U shape, see the dashed blue line in Figure 4.

For the case of free trade, recall from Proposition 6 that the specialization pattern switches at a threshold carbon tax of $\tau_2'(\tau^*)$ because of the change in the relative price of the two goods. Below this threshold, the home country produces the dirty good, so that the carbon tax matters and increases utility. Beyond the threshold utility is higher since the foreign economy produces without damaging the environment much. Since all dirty good production is done abroad, utility is not affected by further increases in the carbon tax.

These results are summarized in the following proposition. The proof can again be found in the appendix.

Proposition 7 *Let the foreign economy be very carbon efficient, $A^Z = 0$, and let the valuation for the environment, β, be intermediate. Then the equilibrium home carbon taxes will be low in autarky. Under free trade they will be set high enough to relocate dirty good production abroad.*

The equilibrium of taxes described in this proposition is a Nash equilibrium. The calculation of the Nash equilibrium is facilitated by the assumption that the foreign economy is very carbon efficient, so that the foreign carbon tax has no effect. The home country taxes however have a strong effect on home utility. The only cause for the increase in the optimal carbon taxes is the change in the trade regime. The intuitive explanation is the one from Proposition 6: free trade makes a much better marginal rate of transformation available to the home economy.

5 The Environmental Kuznets Curve

5.1 Empirics of the EKC

As shown in Dasgupta et al. (2002), the empirical picture on whether the EKC exists and what it looks like is far from clear. Between an optimistic view that low-carbon development is already occurring and a pessimistic view that newly introduced toxics are causing more harm than abatement in old ones is doing good, there is a range of possible scenarios as they illustrate in their Figure 1. Referring to earlier econometric work, Stern (2004) comes to the conclusion that the EKC does not exist empirically. Given the complex interaction of growth and pollution he suggests a more differentiated approach. Dinda (2004) and Carson (2010) also reach the conclusion that no EKC can be observed for CO_2 to date.

Copeland and Taylor (2004) point out that the focus on income as a determinant for pollution is too restrictive. Various effects are at work and often act in opposing directions. The EKC can thus only be understood if the total effect is decomposed into these individual effects. Few empirical studies do this. Those papers which attempt decompositions, such as Hilton and Levinson (1998) and Gale and Mendez (1998) show the complexity of the issue. Even the classical case of a "proven" EKC, that of SO_2 described by Grossman and Krueger (1991), is sensitive to changes in the time period and countries included, see Harbaugh et al. (2002).

5.2 The Theory of the EKC

Guided by a theoretical model, Copeland and Taylor (2004) classifies the explanations into four categories. The first category is "sources of growth". According to this explanation, growth is driven by an increase in different input factors in different stages. Since different input factors imply growth in different sectors of the economy, this will have a differential effect on pollution. Capital-driven industrialization could lead to increasing pollution whereas the human-capital driven rise of the service sector would reduce it again.

The second category is the "income effect". Given variable income elasticities for consumption and a clean environment, consumers first demand mainly consumption and then increasingly a clean environment. This has been modelled in various forms: In John and Pecchenino (1994), environmental quality is a good for which utility is saturated at first. With increasing development the economy starts investing into it. In Andreoni and Levinson

(2001) there is a technological link between consumption of a desired good and abatement of its undesirable byproduct.

The third category is "threshold effects". In the political process or in abatement opportunities, there is a threshold which allows effective reduction of pollution. An example of the first type is Jones and Manuelli (1995) where the internalization of externalities requires advanced institutions which can form only at an advanced stage of development. An example for the second type is Stokey (1998) where there is a threshold level of economic activity below which only the dirtiest technologies can be used.

The final category is "the role of international markets". This is basically the pollution haven effect which allows individual countries to reduce pollution by moving dirty production abroad. In Suri and Chapman (1998) for example, advanced economies can reduce their carbon footprint by offshoring polluting industries to less developed countries. This explanation is the only one which can only be used by a part of countries, since the dirty production must be located somewhere.

An alternative classification would be into demand side effects which includes the income effect as well as the political part of the threshold effect, since the political process does implement the household demands in spite of practical difficulties, and supply side effects which includes sources of growth and the abatement part of the threshold effect since this reflects the production structure.

6 Conclusion

This paper describes how the interaction of international trade and a universal carbon tax can reconcile the desire of developing countries to avoid consumption losses and the urgent need to reduce carbon emissions. A carbon tax would provide an incentive to move energy intensive production to carbon efficient producers. Gains from trade would assure that consumption can be maintained at high levels.

Comparing the developing process of the currently rich countries and those developing now, the combination of the two policies should permit low-carbon development, the combination of rapid growth with low levels of emissions.

The static gains from trade described here may not cover all the benefits of trade. Specialized countries will focus their research on those technologies, where they are already relatively advanced. Dynamic gains from trade could be realized if efficient countries invest in further

driving down their emissions and technologies for "clean" goods are advanced by their trading partners.

References

Andreoni, J. and Levinson, A. (2001). The simple analytics of the environmental kuznets curve. *Journal of public economics*, 80(2):269–286.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46(Supplement 1):878–894.

Carraro, C. and Siniscalco, D. (1993). Strategies for the international protection of the environment. *Journal of public Economics*, 52(3):309–328.

Carson, R. T. (2010). The environmental kuznets curve: Seeking empirical regularity and theoretical structure. *Review of Environmental Economics and Policy*, 4(1):3–23.

Chichilnisky, G. (1994). North-south trade and the global environment. *The American Economic Review*, 84(4):pp. 851–874.

Copeland, B. and Taylor, M. (1994). North-south trade and the environment. *Quarterly Journal of Economics*, 109(3):755–787.

Copeland, B. and Taylor, M. (2004). Trade, growth, and the environment. *Journal of Economic Literature*, 42(1):7–71.

Copeland, B. and Taylor, M. (2005). Free trade and global warming: a trade theory view of the kyoto protocol. *Journal of Environmental Economics and Management*, 49(2):205–234.

Dasgupta, S., Laplante, B., Wang, H., and Wheeler, D. (2002). Confronting the environmental kuznets curve. *The Journal of Economic Perspectives*, 16(1):147–168.

Dinda, S. (2004). Environmental kuznets curve hypothesis: a survey. *Ecological economics*, 49(4):431–455.

Gale, L. and Mendez, J. (1998). The empirical relationship between trade, growth and the environment. *International Review of Economics & Finance*, 7(1):53–61.

Galor, O. and Mountford, A. (2006). Trade and the great divergence: the family connection. *The American economic review*, 96(2):299–303.

Grossman, G. M. and Krueger, A. B. (1991). Environmental impacts of a north american free trade agreement. Working Paper 3914, National Bureau of Economic Research.

Harbaugh, W., Levinson, A., and Wilson, D. (2002). Reexamining the empirical evidence for an environmental kuznets curve. *Review of Economics and Statistics*, 84(3):541–551.

Hilton, F. and Levinson, A. (1998). Factoring the environmental kuznets curve: evidence from automotive lead emissions. *Journal of Environmental Economics and Management*, 35(2):126–141.

John, A. and Pecchenino, R. (1994). An overlapping generations model of growth and the environment. *Economic Journal*, 104(427):1393–1410.

Jones, L. E. and Manuelli, R. E. (1995). A positive model of growth and pollution controls. Working Paper 5205, National Bureau of Economic Research.

Lin, B. and Sun, C. (2010). Evaluating carbon dioxide emissions in international trade of china. *Energy Policy*, 38(1):613 – 621.

Liu, X., Ishikawa, M., Wang, C., Dong, Y., and Liu, W. (2010). Analyses of co2 emissions embodied in japan-china trade. *Energy Policy*, 38(3):1510 – 1518.

Pethig, R. (1976). Pollution, welfare, and environmental policy in the theory of comparative advantage. *Journal of Environmental Economics and Management*, 2(3):160–169.

Stern, D. (2004). The rise and fall of the environmental kuznets curve. *World development*, 32(8):1419–1439.

Stokey, N. (1998). Are there limits to growth? *International Economic Review*, 39(1):1–31.

Suri, V. and Chapman, D. (1998). Economic growth, trade and energy: implications for the environmental kuznets curve. *Ecological economics*, 25(2):195–208.

Xu, M., Allenby, B., and Chen, W. (2009). Energy and air emissions embodied in china-u.s. trade: Eastbound assessment using adjusted bilateral trade data. *Environmental Science and Technology*, 43(9):3378–3384.

Xu, M., Li, R., Crittenden, J. C., and Chen, Y. (2011). Co2 emissions embodied in china's exports from 2002 to 2008: A structural decomposition analysis. *Energy Policy*, 39(11):7381 – 7388.

A Figures

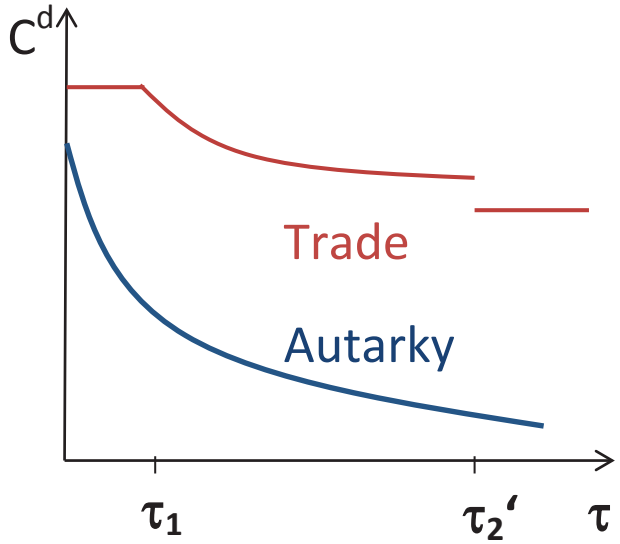

Figure 1: Consumption of the dirty good

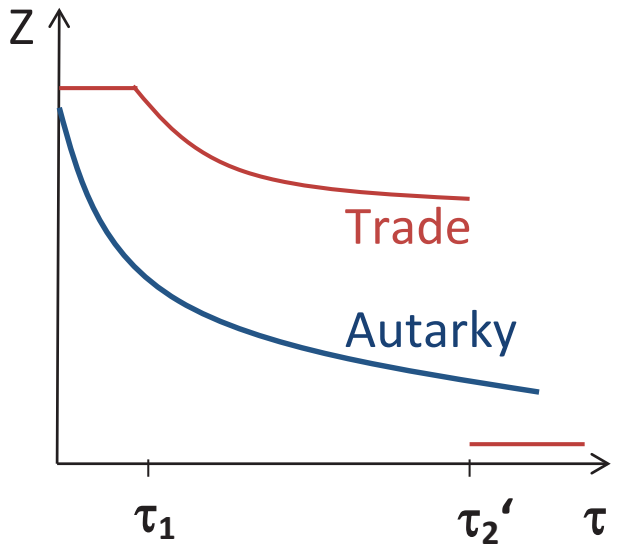

Figure 2: Pollution as a function of carbon taxes

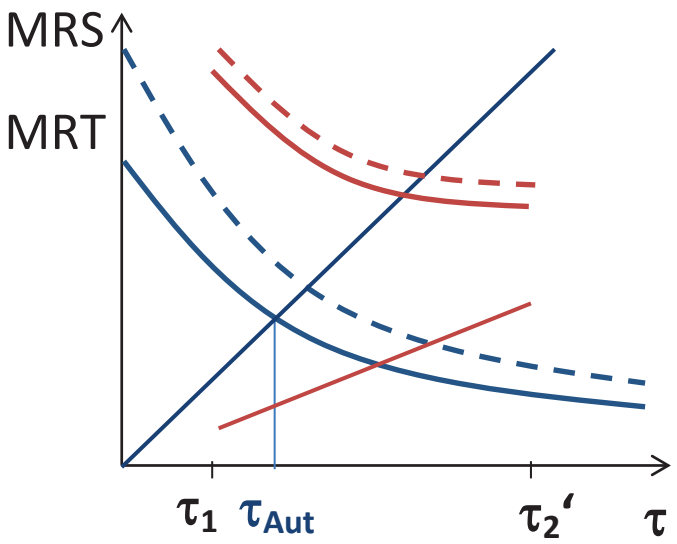

Figure 3: Equilibrium

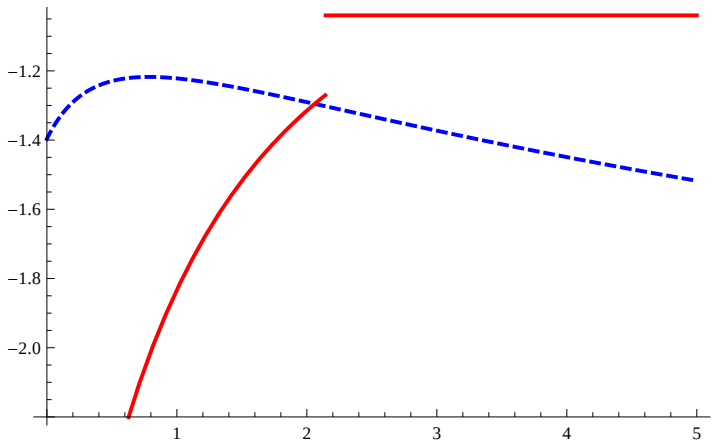

Figure 4: Home country utility as a function of home country carbon taxes. Dashed blue line: Utility in autarky. Solid red line: Utility in free trade.

B Proofs

Proof for Proposition 1:

Households maximize utility (6) subject to the budget constraint (7). First order conditions are:

$$\begin{aligned} \alpha\frac{1}{C^c} - \lambda &= 0 \\ (1-\alpha)\frac{1}{C^d} - \lambda P &= 0 \end{aligned}$$

so that

$$C^c = \frac{\alpha}{1-\alpha} P C^d \tag{20}$$

From the zero profit conditions $wL^d = P^d A^d L^d - \tau Z$ and $wL^c = P^c A^c L^c$ we have

$$\begin{aligned} w &= A^c & (21)\\ P &= \frac{A^c}{A^d} + \tau A^Z \,. & (22) \end{aligned}$$

Using (7), (20), (21) and (22) we can write

$$\begin{aligned} C^c &= \frac{\alpha}{1-\alpha} P \left[\frac{wL - C^c}{P}\right] \\ &= \alpha A^c L \end{aligned}$$

and thus

$$C^d = (1-\alpha) A^d \frac{A^c}{A^c + \tau A^z A^d} L \,.$$

Proof for Proposition 2:

Consider the household maximization. FOCs are:

$$\begin{aligned} \alpha \frac{1}{C^c} - \lambda &= 0 \\ (1-\alpha)\frac{1}{C^d} - \lambda P^i &= 0 \end{aligned}$$

so that

$$\begin{aligned} C^c &= \frac{\alpha}{1-\alpha} P^i C^d & (23)\\ C^{c*} &= \frac{\alpha}{1-\alpha} P^i C^{d*} \,. & (24) \end{aligned}$$

Assume that both countries are fully specialized, the home country producing the dirty good and the foreign country the clean good. This implies $L^d = L$ and $L^{c*} = L^*$ so that production can be written as

$$\begin{aligned} A^d L &= Y^d = C^d + C^{d*} & (25)\\ A^{c*} L^* &= Y^c = C^c + C^{c*} \,. & (26) \end{aligned}$$

The ratio of (25) and (26) yields relative demand:

$$\frac{C^d + C^{d*}}{C^c + C^{c*}} = \frac{A^d L}{A^{c*} L^*} \tag{27}$$

Balanced trade under full specialization implies

$$P^i C^{d*} = C^c \, . \tag{28}$$

Substituting (28) into (23) and (24) we have

$$C^{d*} = \frac{\alpha}{1-\alpha} C^d \tag{29}$$

$$C^{c*} = \frac{\alpha}{1-\alpha} C^c \tag{30}$$

Substituting (24), (29) and (30) into (27) we get

$$P^i = \frac{1-\alpha}{\alpha} \frac{A^{c*} L^*}{A^d L} \, . \tag{31}$$

By analogy with the autarkic home price, equation (22), we know the relative price in the autarkic foreign economy to be $P^* = \frac{A^{c*}}{A^{d*}} + \tau A^{Z*}$. By assumption 2, the international price is smaller than the price in the foreign economy $P^i < P^*$ for all τ. By setting $P^i = P$ and solving for τ, we obtain τ_1. Therefore, the international price is higher than the autarkic price whenever $0 \leq \tau < \tau_1$.

When τ increases to τ_1, the international price equals the domestic prices for the home country, so that it diversifies into the clean good. When τ increases further the two autarkic prices eventually equalize since $A^Z > A^{Z*}$. In this case, both economies produce both goods. τ_2 is obtained by setting $P = P^*$ and solving for τ. At further increases of τ, the relative price will be higher in the home country, so the home country stops producing the dirty good.

Proof for Proposition 3:

(i) Substituting (29) and (30) into (25) and (26) we obtain the following consumption

shares:

$$C^c_{Trade} = (1-\alpha)A^{c*}L^*, \tag{32}$$

$$C^d_{Trade} = (1-\alpha)A^dL, \tag{33}$$

$$C^{c*}_{Trade} = \alpha A^{c*}L^*, \tag{34}$$

$$C^{d*}_{Trade} = \alpha A^dL \tag{35}$$

World pollution is

$$Z_{Trade} = A^Z A^d L\ . \tag{36}$$

Recall from proposition 1:

$$\begin{aligned} C^c_{Aut} &= \alpha A^c L, \\ C^d_{Aut} &= (1-\alpha)A^d \frac{A^c}{A^c + \tau A^z A^d} L \\ Z_{Aut} &= A^Z (1-\alpha) A^d \frac{A^c}{A^c + \tau A^z A^d} L\ . \end{aligned}$$

For $\alpha = 0.5$, $L = L^*$ and $\tau = 0$ and considering assumption 1, we can directly see that more of each good is consumed under trade.

Total world pollution under autarky is given by $Z_{Aut} + Z^*_{Aut}$. For $\alpha = 0.5$, $L = L^*$ and $\tau = 0$ we have

$$Z_{Aut} + Z^*_{Aut} = 0.5L(A^Z A^d + A^{Z*} A^{d*})\ . \tag{37}$$

Under assumption 1 we have $Z_{Trade} > Z_{Aut} + Z^*_{Aut}$.

(ii) Clearly, $\frac{\partial C^d_{Aut}}{\partial \tau} < 0$ and $\frac{\partial Z_{Aut}}{\partial \tau} < 0$.

Proof for Proposition 4: (i) If $\tau > \tau_2$ then, according to proposition 2, the home country is specialized on the clean good while the foreign country produces both goods. In order to compare levels of consumption and pollution, we determine the level of consumption and pollution in this case. To do this we collect all relevant equations.

The first order conditions of the household are (as in the proof for proposition 2):

$$C^c = \frac{\alpha}{1-\alpha} P^* C^d \tag{38}$$

$$C^{c*} = \frac{\alpha}{1-\alpha} P^* C^{d*}\ . \tag{39}$$

The relative price for the dirty good is that of the foreign economy:

$$P^* = \frac{A^{c*}}{A^{d*}} + \tau A^{Z*} \ . \tag{40}$$

The value of goods exchanged is equal:

$$P^* C^d = C_H^{c*};, \tag{41}$$

where C_H^{c*} is the amount of the clean good produced at home and consumed in the foreign economy.

Consumption of the clean good in the foreign economy is thus

$$C^{c*} = C_H^{c*} + C_F^{c*} \ . \tag{42}$$

Production of the clean good is consumed at home as well as in the foreign economy:

$$A^c L = C^c + C_H^{c*} \ . \tag{43}$$

Production of the clean good in the foreign economy is consumed in the foreign economy:

$$A^{c*} L^{c*} = C_F^{c*} \tag{44}$$

Production in the dirty good in the foreign economy is consumed in the foreign economy as well as at home:

$$A^{d*} L^{d*} = C^{d*} + C^d \ . \tag{45}$$

Finally, labor in the foreign economy is allocated to clean and dirty production:

$$L^* = L^{d*} + L^{c*} \ . \tag{46}$$

Given that the price is exogenously determined, the remaining eight equations form a linear equation system in the eight variables C^d, C^c, C^{d*}, C^{c*}, C_H^{c*}, C_F^{c*}, L^{d*}, L^{c*}.

Not making use of assumption 4, lets the resulting expressions look unhandy. Consump-

tion in the foreign economy will be

$$\begin{aligned} C^{d*} &= \frac{1}{2}\frac{-A^c A^{c*} + A^c A^{d*} P^* + 2A^{c*} A^{d*} P^*}{P^*(A^{c*} + A^{d*} P^*)} \\ C^{c*} &= \frac{1}{2}\frac{-A^c A^{c*} + A^c A^{d*} P^* + 2A^{c*} A^{d*} P^*}{A^{c*} + A^{d*} P^*} \; . \end{aligned}$$

Making use of assumption 4, yields the following expressions:

$$C^c_{LCD} = \alpha A^c L, \tag{47}$$

$$C^d_{LCD} = (1-\alpha) A^c \frac{A^{d*}}{A^{c*}} L, \tag{48}$$

$$C^{c*}_{LCD} = \alpha A^{c*} L^*, \tag{49}$$

$$C^{d*}_{LCD} = (1-\alpha) A^{d*} L^*, \tag{50}$$

$$Z_{LCD} = A^{z*} A^{d*} L^{d*} = 0 \; . \tag{51}$$

where the index $_{LCD}$ indicates the low-carbon development scenario. Applying assumption 3 to these results and to the carbon leakage scenario, equations (32) to (36), and applying assumption 1, we see that consumption and pollution is lower under low-carbon development.

(ii) Comparing the values of the low-carbon development scenario with those of the "developing country nightmare" scenario (variables with the index $_{Aut}$) shows that consumption in the clean good is equal in the two scenarios. For high values of τ however, consumption in the dirty good in the "Nightmare" scenario is lower than in the low-carbon development scenario. Pollution is positive in the nightmare scenario since the home country produces some of the dirty good. Under assumption 4, pollution is zero in the low-carbon development scenario.

Proof for Proposition 5: Comparing results in the low-carbon development scenario with those in benchmark (autarky scenario and $\tau = 0$) yields the result. Note that from assumption 1 we have $A^{d*} < A^d$ and $\frac{A^c}{A^{c*}} < 1$.

MRS and MRT in the Case of Autarky

As shown in Proposition 1, consumption and pollution in the case of autarky is given by $C^c = \alpha A^c L$, $C^d = (1-\alpha) A^d \frac{A^c}{A^c + \tau A^z A^d} L$ and $Z = A^Z C^d$. Since $C(\tau) = u(C^c(\tau), C^d(\tau)) = \alpha \ln(C^c(\tau)) + (1-\alpha)\ln(C^d(\tau))$ we have $C_\tau = \frac{\alpha C^d_\tau}{C^d(\tau)}$. The marginal rate of transformation is

therefore

$$\frac{C_\tau}{Z_\tau} = \frac{\alpha C_\tau^d}{C^d(\tau)} \frac{1}{A^Z C_\tau^d} = \frac{\alpha}{A^Z C^d(\tau)} \ .$$

This function is increasing in τ. The MRS is decreasing in τ. This follows directly from the concavity of U, since a higher tax rate increases public good provision (less pollution) and decreases the private good.

Proof for Proposition 6

From Proposition 2 we know that prices in autarky in the two countries are $P = \frac{A^c}{A^d} + \tau A^Z$ and $P^* = \frac{A^{c*}}{A^{d*}} + \tau^* A^{Z*}$ and the international price in case of full specialization is $P^i = \frac{1-\alpha}{\alpha} \frac{A^{c*} L^*}{A^d L}$. As long as $P < P^i$, countries are fully specialized with the home country producing the dirty good. At $P = P^i$, the home country starts diversifying, so that τ_1 is the value at which these two prices are equal. If the home country increases the tax rate so that the relative price exceeds P^*, specialization reverses.

$$\tau_2' = \frac{1}{A^Z} \left(\frac{A^{c*}}{A^{d*}} + \tau^* A^{Z*} - \frac{A^c}{A^d} \right)$$

is therefore the tax rate which sets $P = P^*$.

The decomposition of the reduction in pollution is straightforward:

$$\begin{aligned} Z_1 - Z_2 &= A^Z C_1^d - A^{Z*} C_2^d \\ &= (A^Z - A^{Z*}) C_1^d + A^{Z*} (C_1^d - C_2^d) \ . \end{aligned}$$

Proof for Proposition 7

Since $A^{Z*} = 0$, the foreign carbon tax has no effect. The environmental effect is thus fully determined by home country taxes. Let us first define the two utility functions. With C_{Aut}^d, C_{Aut}^c and Z_{Aut} as defined in Proposition 1, we have

$$U_{Aut}(\tau, \beta) = \alpha \ln(C_{Aut}^c) + (1-\alpha) \ln(C_{Aut}^d(\tau)) - \beta(Z_{Aut}(\tau) + 0) \ . \tag{52}$$

Utility in the case of free trade requires a case distinction at τ_2':

$$U_{Trade}(\tau,\beta)=\begin{cases}\alpha\ln(C^c_{T1}(\tau))+(1-\alpha)\ln(C^d_{T1}(\tau))-\beta(Z_{T1}(\tau)+0), & \text{if } \tau<\tau_2'\\ \alpha\ln(C^c_{T2}(\tau))+(1-\alpha)\ln(C^d_{T2}(\tau))-\beta(Z_{T2}(\tau)+0), & \text{if } \tau\geq\tau_2'\ .\end{cases} \tag{53}$$

Let $\tau^{opt}_{Aut}(\beta)$ denote the optimal value of the carbon tax set by the government in autarky for given β. It is defined by

$$\max_{\tau} U_{Aut}(\tau,\beta)\ . \tag{54}$$

$\tau^{opt}_{Trade}(\beta)$ is defined analogously for the free trade scenario.

We now have to show that there are $\beta_{\min}<\beta_{\max}$ such that

$$(i)\quad \forall\beta<\beta_{\max}\quad \tau^{opt}_{Aut}(\beta)<\tau_2'\ , \tag{55}$$

$$(ii)\quad \forall\beta>\beta_{\min}\quad \tau^{opt}_{Trade}(\beta)=\tau_2'\ . \tag{56}$$

(i) From proposition 1, we have

$$\begin{aligned} C^c_{Aut} &= \alpha A^c L,\\ C^d_{Aut} &= (1-\alpha)A^d\frac{A^c}{A^c+\tau A^z A^d}L\ ,\\ Z_{Aut}+Z^*_{Aut} &= A^Z(1-\alpha)A^d\frac{A^c}{A^c+\tau A^z A^d}L+0\ . \end{aligned}$$

Utility is given as

$$U_{Aut}(\tau)=\alpha\ln(C^c_{Aut})+(1-\alpha)\ln(C^d_{Aut})-\beta(Z_{Aut}+Z^*_{Aut})\ . \tag{57}$$

The optimal carbon tax in autarky is thus

$$\tau^{opt}_{Aut}=\beta A^c L-\frac{A^c}{A^Z A^d}\ . \tag{58}$$

Therefore

$$\beta_{\max}=\frac{1}{A^c L}\left(\tau_2'+\frac{A^c}{A^Z A^d}\right)\ . \tag{59}$$

(ii) Let $U_{T1}(\tau,\beta)$ and $U_{T1}(\tau,\beta)$ be the utility functions associated with the two sub-

functions in (53). Then $\beta_{\min}$ is defined as

$$U_{T1}(\tau^{opt}_{Trade}(\beta_{\min}), \beta_{\min}) = U_{T1}(\tau_2', \beta_{\min}) \; . \tag{60}$$

This is the minimal value for β, where the home government sets carbon taxes high enough to enter the specialization pattern, where it doesn't produce the dirty good.

To determine $\beta_{\min}$, we need to solve for the consumption variables ($C^c_{T1}(\tau)$ etc.) for the specialization pattern, where the home economy produces both goods and the foreign economy is specialized on the clean good. The equation system is obtained in a similar fashion to the proof of Proposition 4:

$$\begin{aligned}
C^c &= \frac{\alpha}{1-\alpha} P C^d && (61)\\
C^{c*} &= \frac{\alpha}{1-\alpha} P C^{d*} && (62)\\
P &= \frac{A^c}{A^d} + \tau A^Z && (63)\\
PC^{d*} &= C^c_F && (64)\\
C^c &= C^c_H + C^c_F && (65)\\
A^{c*} L^* &= C^{c*} + C^c_F && (66)\\
A^c L^c &= C^c_H && (67)\\
A^d L^d &= C^{d*} + C^d && (68)\\
L &= L^d + L^c \; . && (69)
\end{aligned}$$

Given that the price is exogenously determined, the remaining eight equations form a linear equation system in the eight variables C^d, C^c, C^{d*}, C^{c*}, C^c_H, C^c_F, L^d, L^c.

A similar procedure can be applied to solve for the consumption values like $C^c_{T2}(\tau)$ above τ_2' when the home country is specialized on the clean good and the foreign countries produces both.

Unfortunately, the values like $C^c_{T1}(\tau)$ depend on τ in such a way, that the resulting value for τ^{opt}_{Trade} are extremely long expressions. The resulting $\beta_{\min}$ from equation (60) cannot be compared to $\beta_{\max}$.

So in order to prove that there is a parameter constellation where conditions (55) and (56) are met simultaneously, we give an example. Consider the following parameters: $A^{d*} = 1, A^d = 2, A^{c*} = 2, A^c = 1, A^Z = 0.7, A^{Z*} = 0, L = 1, \alpha = 0.5, \beta = 1.5$. Then the utility

functions are given in Figure (4). The optimal carbon taxes in the two regimes are $\tau_{Trade}^{opt} = \tau_2' = \frac{1}{A^Z}\left(\frac{A^{c*}}{A^{d*}} - \frac{A^c}{A^d}\right) = 2.14$ and $\tau_{Aut}^{opt} = \beta A^c L - \frac{A^c}{A^Z A^d} = 0.79$.