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Abstract:

Is it possible to combat global climate change through North-to-South technology transfer even without a global climate treaty? Or do carbon leakage and the rebound effect imply that it is possible to take advantage of technological improvements under the umbrella of a global arrangement only? For answering these questions a world with full international co-operation is compared with a world, where countries act non-cooperatively. More precisely, in case of non-cooperation two cases are discussed. The first one is called Kyoto-plus and the second one labeled Kyoto-reversed. Kyoto-plus means that the North decides: (1) to unilaterally reduce its domestic greenhouse gas emissions and (2), to transfer technological knowledge to the South. If Kyoto-reversed is considered, the North decides on transferring technology while the South commits itself to reduce emissions. Rebound and leakage effects hinder a sustainable and welfare improving solution of the climate problem.

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1 Introduction

The last COP meeting in December 2011 at Durban once again has demonstrated that the world society presently is unable to establish an international agreement on greenhouse gas abatement, which extends the existing Kyoto Protocol. This has redirected the discussion to the role, the development, the implementation and the transfer of technologies can play in combating global warming. One reason is that technology transfer can be successfully achieved through bilateral arrangements and does not need full international cooperation. A second one is that new technologies are at core in fighting the threat of climate change. Any stabilization of the atmospheric carbon concentration at levels below catastrophic ones requires eliminating carbon emissions almost completely within the next two centuries (see IPCC, 2001), and the most effective way to de-carbonize the world economy is to develop and to use climate-friendly technologies. These could include improvements in energy efficiency, but also advanced technologies for generating electricity or carbon capturing and sequestration (CCS).

Today, the potential for inventing more energy-efficient and climate-related technologies is highest in industrialized countries, but the need for such technologies is most urgent in the developing world and the fast growing economies of Asia and Latin America. The Energy Information Administration (2011) projects that by 2035 carbon emissions of non-OECD countries will exceed those of the OECD member states by more than 100%, while technological innovations still will occur in a few, highly industrialized countries only. Not surprisingly, a large number of both scientific and political commentaries, among which the U.S. during the Bush administration was the most prominent one, advocate the transfer of technologies from the developed to the developing world.

In a study, which covers the period from 1998 to 2003 and uses patent counts to measure both the output and the international transfer of technologies, Dechezlepretre et al. (2011)[2] found that the majority of technology transfers is between the developed countries. North-to-South transfers account for less than 20 % of all, while South-to-South transfers are al-

[2] The authors argue that patent counts from the EPO/OECD World Patent Statistical Database (PATSTAT) are the only indicator available today that provides a comprehensive view on innovation and technology diffusion on a global scale.

most inexistent. This suggests a huge potential for extending North-to-South transfers further. But what are the effects of transferring technologies from the industrialized countries to the developing ones on global emissions and regional welfare? And under which circumstances does the North have an incentive at all for transferring technologies? Answering these questions for a world, where technology transfer from North to the South is combined either with unilateral climate policies or full cooperation in the solution of the global climate problem is at the center of this analysis.[3]

For more than twenty years the economic literature discusses how the transfer of technologies can be helpful in avoiding the adverse effects of global climate change. Some papers take trade aspects into account (for an overview, see Copeland and Taylor, 2004). This is of particular importance, since international transfers such as providing technical assistance for coping with climate change, can lead to what is called a transfer paradox (see Takarada, 2005). Lee (2001) for example discloses such a paradox in the sense that, despite of the transfer, the industrialized donor gains economic welfare while the recipient developing country loses welfare. Terms-of-trade deterioration is the principal reason for such a result as is recognized since the pioneering work of Bhagwati et al. (1983).

A part of the extensive literature on the provision of public goods also discusses the issue of technology transfer, typically within a strategic framework, where trade issues are neglected. Two papers are of particular interest. Buchholz and Konrad (1994) analyze at which level technological transfers will be realized under either cooperative or non-cooperative environmental policies. They show that if the countries with the inferior technology adopt an improved one, the quality of the environment might deteriorate nonetheless. Stranlund (1996) considers the case where the level of the technology transfer is chosen in the first stage, and abatement activities are non-cooperatively determined in the second one. As a result, both the quality of the global environment and the welfare of the donor country are improved.

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[3] We are not discussing the aspect of incentive compatibility of technology transfers for participation and compliance in climate change mitigation. For a discussion, see Barrett (2006), or, in the more general context of adaptation funding, Buob and Stephan (2012).

A third strand of literature applies Computable General Equilibrium (CGE) models for analyzing numerically the effects of technology transfers. Much of this literature bases on the work of Yang (1999) as well as Nordhaus and Yang (2006) and applies some variant of the RICE model of integrated assessment of global climate change (see Nordhaus and Boyer, 2000). Mostly the results reported sound encouraging. Recently, Aronsson et al. (2010) showed: If the countries of the South are free of obligations for curbing greenhouse gas emissions, then both the North and the South will profit from technology transfers through a better environment and higher welfare. A closer look on these analyses reveals that carbon energy is not an input into production and technological change has no effect other than reducing costs of greenhouse gas abatement. As such transferring technology diminishes the cost-of-abatement differential across regions and allows for abating greenhouse gases more efficiently. This explains why from the perspective of the North technology transfer is motivated even if transfer costs are non-negligible.[4]

Technology transfer is not only a mean for lowering abatement costs. It can also contribute to economic growth, for example through increasing the energy-efficiency of production. Data on the transfer of patents show that between 1978 and 2003 the share of climate-related patents always stood below 2% of the total (see Dechezlepretre et al., 2011). The majority of transfers applied to patents on more energy efficient technologies. This motivates a first point of departure from the existing literature on technology transfers and greenhouse gas mitigation. We explicitly include carbon energy into our framework and consider the North-to-South transfer of more energy-efficient technologies. However, increasing the energy efficiency through using more efficient technologies can let greenhouse gas emissions rise (see Brännlund et al., 2007). The intuition is that improvements in energy efficiency create an income effect through which demand for energy is stipulated. Or to phrase it differently, efficiency gains wipe out the emission reductions, and hence, a "rebound effect" occurs.

[4] The importance of cost-efficiency is acknowledged in the UN Framework Convention on Climate Change (UNFCCC). Article 3.3 states that climate policy should "ensure global benefits at the lowest possible cost". One way to increase cost-efficiency is the transfer of technologies at least as long as there are cost differentials between Annex I and non-Annex I countries (see Aronsson et al., 2010).

Most of the literature on technological change and the provision of public goods, which is relevant in our context, does not consider international trade. However, since technological change affects the demand for carbon energy and hence the terms-of-trade, which in turn has an impact of welfare, trade in carbon energy should be explicitly taken into account. This motivates the second point of departure from the existing literature. We assume that carbon energy, which includes oil, gas and coal mainly, is traded on a single integrated world market.[5] However, if there is international trade in carbon energy and other energy-intensive basic materials, carbon leakage can occur. For example, unilateral greenhouse gas abatement in one region can because of terms-of-trade effects let the unconstraint region increase its imports of carbon energy and hence emit more than it would otherwise (for a discussion, see Burniaux and Oliveira-Martins, 2000).

The rest of the paper is organized as follows. Section 2 presents our theoretical framework. It is kept deliberately simple, but covers international trade in carbon energy as well as North-to South transfer of more energy-efficient technologies. Section 3 discusses two possible states of the world: one, where regions do not cooperate in the solution of the global climate problem, but unilaterally decide on climate policies and technology transfers; one, where regions fully cooperate and simultaneously decide on Pareto-efficient mitigation policies. It is shown that rebound and leakage effects hinder a sustainable and welfare improving solution of the climate problem. Finally, Section 4 concludes.

2 Getting started: a simple static model

To fix ideas, let the world be divided into two regions. For vividness they will be called North and South. North (N) consists of the OECD countries plus the former Soviet Union. Roughly, this corresponds to the ANNEX I parties. South (S) covers the rest of the world, hence includes those countries, which the Kyoto Protocol exempts from the duty of greenhouse gas abatement.

Each region $n = N,S$ produces a homogenous output which can be consumed domestically and can be used to cover costs of energy supply. To keep considerations as simple as possi-

[5] Of course this is an oversimplification of reality. It is inspired, however, by Nordhaus´ (2009) observation that there is only a single, integrated world market for oil.

ble, technological knowledge and carbon energy are the only inputs into regional production. Formally, for each region n gross domestic production (GDP) is characterized by the function $F_n(Z_n, e_n)$, where the region's energy inputs e_n are measured in carbon equivalents to energy consumption, hence directly govern the emissions of greenhouse gases such as carbon dioxide. Z_n denotes the region's stock of technological knowledge and rules the energy efficiency of regional production. This implies in particular that the innovation of new technologies can increase the energy efficiency and/or might reduce the carbon intensity of domestic production. This is nothing else than saying that each region can influence welfare through investing into technological knowledge as well as by investing into environmental capital through greenhouse gas mitigation.

Technological knowledge is different from other inputs such as raw materials, energy, labor or physical capital. To capture some of its essential features let us assume (see Gillingham et al., 2007):

(1) Once installed in a region, technological knowledge is a non-rival input into regional production, and hence can be applied as often as desired.[6]

Given that regional production is linear homogenous in energy this implies

(2.1) $$F_n(Z_n, e_n) = \frac{\partial F_n}{\partial e_n} e_n.$$

(2) Technological knowledge is appropriable to the single region.

That means, regions have the ability to capture all benefits derived from inventing technologies and can exclude other regions from using that technology. This implies that transferring technologies requires a policy decision.

(3) Technology transfer is costless.

6 For example, once the laws of thermodynamics, which form the scientific basis of any combustion engine, have been discovered, they can be applied as often as desired. This discriminates technological knowledge from human capital. In the latter case knowledge is inherently tied to a person, hence can be used only, if that person is present (see Romer, 1990).

Typically, transferring technologies causes costs. Examples are costs of installation and maintenance, costs to modify existing technologies and to make the new ones appropriate for use in the recipient's economy. However, since we are interested on the strategic interaction between mitigation and technology transfers, for sake of simplicity it is assumed in the following that new technologies are transferred free of costs.

Carbon energy is produced in both regions and is traded on an open international market. Therefore, if s_n denotes the supply of region *n*, the world energy market is in equilibrium, if

(2.2) $$s_N + s_S - e_N - e_S = 0.$$

Carbon energy is Janus-faced. The more energy is put into production, the higher is the domestic output, but simultaneously, the higher are greenhouse gas emissions. This drives global climate change, which is a public bad and negatively affects regional welfare.

In principle, there are two categories of climate change impacts. On the one hand there are impacts which can directly be measured in terms of output losses. For example, in the case of agriculture prices exist, which allow assigning market values to these output losses. Consequently, these impacts are termed market damages. On the other hand there are so-called non-market damages, such as species losses or catastrophic changes in the ocean currents, which cannot be directly expressed in terms of a national accounting system (see Manne and Stephan, 2005).

This paper concentrates on market damage of climate change only. Or to phrase it differently, impacts of climate change materialize in losses of regional gross production. Therefore, let $\Phi_n(e_N + e_S)$, with $\Phi_n' < 0$ and $\Phi_n'' < 0$, denote the regional climate damage factor, which is a function of global emissions and measures the fraction of conventional domestic output that is at disposal in region *n*. That means, the more carbon energy is consumed world-wide, the higher is the stock of globally accumulated greenhouse gas emissions, and hence, the lower will be the fraction of conventional wealth that is available to region *n*. The remaining fraction $\Phi_n(e_N + e_S)F_n(Z_n, e_n)$ is called green GDP.

In each region *n* green GDP has to cover: (1) regional consumption c_n, (2) costs of energy supply, which are a strictly increasing function $g_n(s_n)$ of regional energy output s_n and which are measured in units of domestic GDP, and (3) potential deficits from trading carbon energy. That means

(2.3) $$\Phi_n(e_N + e_S)F_n(Z_n, e_n) - g_n(s_n) + p(s_n - e_n) - c_n = 0,$$

where *p* denotes the world market price of carbon energy.

3 Analysis

In the following, let us consider two possible states of the world: one, where regions do not cooperate in the solution of the global climate problem, but act as if they were Nash players, who unilaterally decide on climate policies and technology transfers; one, where regions fully cooperate and simultaneously decide on Pareto-efficient mitigation policies.

3.1 Unilateral climate policies and North-to-South technology transfers

In case of non-cooperation we discuss two cases. The first one is called Kyoto-plus, and reflects a situation as proposed by the European Union, where the North tightness its emission targets and supplies technologies to the South. The second one is called Kyoto-reversed and reflects a state of the world, where the South no longer is free of obligations to curb greenhouse gas emissions. I.e., not only more energy-efficient technologies, but also the duty of greenhouse gas abatement is shifted from North to South. In both cases a non-cooperative 2-stage game is employed. Kyoto-plus (Section 3.1.1) means that in stage 1 the North decides: (1) to unilaterally reduce its domestic greenhouse gas emissions and (2), to transfer technological knowledge to the South. In stage 2 the South chooses its welfare maximizing inputs of carbon energy into regional production. If Kyoto-reversed (Section 3.1.2) is considered, in stage 1 the North decides on transferring technology, while the South commits itself to reduce emissions in stage 2.

As usual, sub-game perfect equilibria are obtained through backward induction. That means, given the decisions of the first stage, in the second one, regions independently maximize welfare. Therefore, before analyzing the two cases separately, let us first consider some properties, which generally follow, if regions maximize welfare without reflecting that their decision affects the welfare of the other region. Since by assumption climate change directly affects production and not utilities, regional consumption (see (2.3)) can be viewed as proxy of regional welfare, i.e., in case of non-cooperation regions independently solve the problem

$$\mathrm{Max}\{\Phi_n(e_N+e_S)F_n(Z_n,e_n)-g_n(s_n)+p(s_n-e_n)\}.$$

Necessary conditions for an interior solution are

(3.1) $$\Phi_n'(e_N+e_S)F_n+\Phi_n(e_N+e_S)\frac{\partial F_n}{\partial e_n}-p=0,$$

(3.2) $$-g_n'(s_n)+p=0.$$

Condition (3.2) indicates: (1) regional supply of carbon energy $s_n(p)$ is a strictly increasing function of price *p*, and (2), in equilibrium marginal costs of energy supply are identical across regions. Condition (3.1) reflects that changing unilaterally the input of carbon energy has two opposite effects. On the one hand it affects the regions' marginal productivity of energy and it has an impact on the marginal damages of climate change on the other.

Now, since $p\ \geq 0$ from condition (3.1) follows

(3.3) $$\Phi_n'F_n+\Phi_n\frac{\partial F_n}{\partial e_n}=\frac{\partial F_n}{\partial e_n}(\Phi_n'e_n+\Phi_n)\geq 0.$$

The left side implies that in optimum the marginal green productivity of carbon energy, $\Phi_n\frac{\partial F_n}{\partial e_n}$, has to be bigger than marginal damages, $-\Phi_n'F_n$, measured in absolute terms. The right side implies

$$\frac{d\Phi_n}{d(e_N+e_S)}\frac{e_n}{\Phi_n}\geq -1,$$

which means that in equilibrium the elasticity of regional climate damages has to be bigger than -1. Or to phrase it differently: the percentage change in climate damages has to be smaller than the percentage change in energy consumption.

Condition (3.1) implicitly defines the regional demand for carbon energy e_n as function of the world market price *p,* demand e_{-n} of the other region and the regional technology stock Z_n, i.e., $e_n = E_n(p, e_{-n}, Z_n)$. Taking the total differential gives

$$de_n = \frac{\partial e_n}{\partial p} dp + \frac{\partial e_n}{\partial e_{-n}} de_{-n} + \frac{\partial e_n}{\partial Z_n} dZ_n.$$

The first term represents the price effect, the second one is the leakage effect and the last one indicates that there might be a rebound effect.

Because of condition (2.1), the price effect is negative,

(3.4) $$\frac{\partial e_n}{\partial p} = \frac{1}{\Phi_n'' F_n + 2\Phi_n' \frac{\partial F_n}{\partial e_n}} < 0.$$

Hence the demand for carbon energy will decrease, if world markets prices rise ceteris paribus. The second term is determined by

(3.5) $$\frac{\partial e_n}{\partial e_{-n}} = -\frac{\Phi_n'' F_n + \Phi_n' \frac{\partial F_n}{\partial e_n}}{\Phi_n'' F_n + 2\Phi_n' \frac{\partial F_n}{\partial e_n}} = -\frac{\Phi_n'' e_n + \Phi_n'}{\Phi_n'' e_n + 2\Phi_n'},$$

which obviously implies

$$0 > \frac{\partial e_n}{\partial e_{-n}} > -1 .$$

That means, if the other region reduces the input of carbon energy, then the region under consideration reacts by extending its inputs of carbon energy into production, but by less than full degree. This indicates leakage.

Finally, note that

(3.6) $$\frac{\partial e_n}{\partial Z_n} = -\frac{\Phi_n' \frac{\partial F_n}{\partial Z_n} + \Phi_n \frac{\partial^2 F_n}{\partial e_n \partial Z_n}}{\Phi_n'' F_n + 2\Phi_n' \frac{\partial F_n}{\partial e_n}} = -\frac{\frac{\partial^2 F_n}{\partial e_n \partial Z_n}}{\frac{\partial F_n}{\partial e_n}} \frac{(\Phi_n' e_n + \Phi_n)}{\Phi_n'' e_n + 2\Phi_n'} > 0$$

is positive as follows from condition (3.3). In other words, due to an increase in energy efficiency more energy will be used as input into production and hence a rebound effect is observed.

3.1.1 Kyoto-plus

The Kyoto-plus scenario assumes that in the first stage the North simultaneously decides on own mitigation and technology transfers. I.e., at beginning of stage 2 technology transfers dZ_S, which are measured as changes of the South's technology stock, as well as changes in the North's input of carbon energy, de_N, are given. Hence, condition (3.1) together with the market clearance condition (2.2) after some manipulations (see Appendix) determine the following system of linear equations, which characterizes the South´s decision problem in stage 2:

(3.7) $$\begin{pmatrix} (S_N' + S_S') & -1 \\ -\frac{\partial e_S}{\partial p} & 1 \end{pmatrix} \begin{pmatrix} dp \\ de_S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{\partial e_S}{\partial e_N} & \frac{\partial e_S}{\partial Z_S} \end{pmatrix} \begin{pmatrix} de_N \\ dZ_S \end{pmatrix}.$$

By using Cramer's rule we get

(3.8) $$dp = \frac{1+\frac{\partial e_S}{\partial e_N}}{S_N'+S_S'-\frac{\partial e_S}{\partial p}} de_N + \frac{\frac{\partial e_S}{\partial Z_S}}{S_N'+S_S'-\frac{\partial e_S}{\partial p}} dZ_S,$$

(3.9) $$de_S = \frac{\frac{\partial e_S}{\partial p}+(S_N'+S_S')\frac{\partial e_S}{\partial e_N}}{S_N'+S_S'-\frac{\partial e_S}{\partial p}} de_N + \frac{(S_N'+S_S')\frac{\partial e_S}{\partial Z_S}}{S_N'+S_S'-\frac{\partial e_S}{\partial p}} dZ_S.$$

As condition (3.8) demonstrates, both North-to-South technology transfer and unilateral climate policy affect the world market price of carbon energy, but overall effects are not clear. (1) The numerator of the first term on the right side corresponds to the net impact, changing energy consumption in the North has on prices. Since $0 > \frac{\partial e_S}{\partial e_N} > -1$, it is positive, and hence, world market prices ceteris paribus will fall, if the North decides reducing its inputs of carbon energy. (2) The numerator of the second term on the right side reflects that transferring technologies to the South will stipulate the South's demand of carbon energy, and hence, the world market price of carbon energy ceteris paribus will rise.

This indicates that we will observe both a leakage and rebound effect. This becomes more obvious, if we consider condition (3.9). As the second term on the right hand side shows, increasing the energy efficiency in the South through technology transfer will stipulate the demand for carbon energy, hence will lead to higher carbon emissions in the South. This is what the literature calls a rebound effect.

Recalculation of the first term of equation (3.9) gives

$$0 > -\frac{(S_N'+S_S')(-\frac{\partial e_S}{\partial e_N})-\frac{\partial e_S}{\partial p}}{(S_N'+S_S')-\frac{\partial e_S}{\partial p}} > -\frac{(S_N'+S_S')-\frac{\partial e_S}{\partial p}}{(S_N'+S_S')-\frac{\partial e_S}{\partial p}} = -1,$$

and hence, there is leakage. However, the leakage effect does not fully compensate the reduction of emissions, the North has decided on in stage 1. Consequently, without technology transfer to the South global emissions would be reduced. In other words, the terms-of-trade effect solely would not imply that globally accumulated emissions will rise.

Nonetheless, Kyoto-plus could turn out a bad policy, both for the global climate and the North. First, the leakage and the rebound effect together may wipe out the mitigation efforts of the North. This might result in higher global greenhouse gas emissions than without the policy intervention of the North (see condition (3.9)). Second, while the North has to bear the costs of greenhouse gas abatement, eventually without gaining benefit from a reduction of climate damages, this could negatively affect the North's welfare. Therefore, let us consider stage 1 and discuss: (1) Which conditions grant that global emissions will fall despite of technology transfers to the South? (2) Under which conditions is Kyoto-plus Pareto improving?

First, suppose $de_S + de_N \leq 0$. This requires (see (3.9))

$$(S_N' + S_S' + (S_N' + S_S')\frac{\partial e_S}{\partial e_N})de_N + (S_N' + S_S')\frac{\partial e_S}{\partial Z_S}dZ_S \leq 0,$$

hence

(3.10) $$dZ_S \leq -\frac{1+\frac{\partial e_S}{\partial e_N}}{\frac{\partial e_S}{\partial Z_S}}de_N.$$

Therefore there is an upper limit on North-to-South technology transfer, which depends on the net-effect of the emission reduction policy of the North as well as the impact of technology transfers on carbon inputs in the South. Or to phrase it differently, the smaller is the leakage effect and the smaller is the rebound effect, the more technology can be transferred to the South, without increasing global greenhouse gas emissions.[7]

Note further, if $de_N < 0$, conditions (3.8) and (3.10) imply that $dp \leq 0$. Or to put it differently, leakage and rebound effects are not strong enough such that there will be no impact on world market prices of carbon energy.

Next, let us discuss the second question from above. Condition (2.3) implies

$$dc_n = \left(\Phi'_n F_n + \Phi_n \frac{\partial F_n}{\partial e_n} - p\right) de_n + \Phi'_n F_n de_{-n} + \Phi_n \frac{\partial F_n}{\partial Z_n} dZ_n + (p - g'_n) ds_n + (s_n - e_n) dp,$$

or because of conditions (3.1) and (3.2) as well as the assumption: $dZ_N = 0$

$$\text{(3.11)} \qquad dc_S = \Phi'_S F_S de_N + \Phi_S \frac{\partial F_S}{\partial Z_S} dZ_S + (s_S - e_S) dp,$$

$$\text{(3.12)} \qquad dc_N = \Phi'_N F_N de_S + (s_N - e_N) dp.$$

Now suppose that technology transfers are low enough such that condition (3.10) is fulfilled. Then the impact of North-to-South transfers on world market prices is negligible, and the South in any case can profit, since $dZ_S > 0$, $de_N < 0$. If, however, condition (3.10) is not satisfied, then world market prices of carbon energy will rise and the South will profit for sure only, if the North is net-importer and the South is net-exporter of carbon energy.

Under Kyoto-plus assumptions the North has for economic reasons almost no incentive at all to transfer technologies to the South. As condition (3.12) indicates, the North could profit only, if the price effect is negative and if the leakage effect is moderate. This represents a dilemma. Even if (3.10) is fulfilled, and hence global emissions drop, condition (3.12) implies

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7 Using conditions (3.5) and (3.6) this gives $dZ_S \leq \frac{\frac{\partial F_S}{\partial e_S}}{\frac{\partial F_S}{\partial Z_S}} \frac{\Phi'_S e_S}{\Phi'_S e_S + \Phi_S} de_N$. I.e., the upper limit on technology transfer depends on the marginal rate of substitution between technology and energy on the one hand and energy consumption as well as marginal damages on the other.

$$dc_N \leq -\Phi'_N F_N de_S < 0,$$

which is negative because of leakage (see (3.9)).

3.1.2 Kyoto-reversed

Under Kyoto-reversed assumptions the duty of reducing greenhouse gas emissions is shifted from Annex I to non-Annex I countries. That means, in the first stage the North decides to transfer technologies, while the South commits itself on climate mitigation. Hence, at beginning of stage 2 technology transfers dZ_S as well as changes in the South's input of carbon energy de_S are given.[8] Therefore, condition (3.1) together with the market clearance condition (2.2) after some manipulations now gives

(3.7a) $$\begin{pmatrix} (S'_N + S'_S) & -1 \\ -\frac{\partial e_N}{\partial p} & 1 \end{pmatrix} \begin{pmatrix} dp \\ de_N \end{pmatrix} = \begin{pmatrix} de_S \\ \frac{\partial e_N}{\partial e_S} de_S \end{pmatrix}.$$

By using Cramer's rule we get

(3.8a) $$dp = \frac{1 + \frac{\partial e_N}{\partial e_S}}{S'_N + S'_S - \frac{\partial e_N}{\partial p}} de_S.$$

which, because of $0 > \frac{\partial e_N}{\partial e_S} > -1$, implies falling prices, if the South reduces emissions.

Falling prices ceteris paribus stipulate rising demand for carbon energy in the North. Indeed, from (3.7a) by applying Cramer's rule again we obtain

(3.9a) $$de_N = \frac{\frac{\partial e_N}{\partial p} + (S'_N + S'_S)\frac{\partial e_N}{\partial e_S}}{S'_N + S'_S - \frac{\partial e_N}{\partial p}} de_S,$$

which means that now emissions in the North will rise, if emissions in the South are reduced. However, the increase will be less than unity such that accumulated emissions nonetheless will fall.

8 Obviously, this creates a participation problem. We will return to this issue in the conclusions.

Finally, let us discuss, how regional consumption changes under Kyoto-reversed assumptions. Conditions (2.3), (3.1) and (3.2) as well as $dZ_N = 0$ imply

(3.11a) $$dc_S = \Phi_S' F_S de_N + \Phi_S \frac{\partial F_S}{\partial Z_S} dZ_S + (s_S - e_S)dp,$$

(3.12a) $$dc_N = \Phi_N' F_N de_S + (s_N - e_N)dp.$$

If, as was supposed above, the North is net-importer of carbon energy and the South is net exporter, then the South nonetheless might profit, provided technology transfer is high enough. The North in any case can profit for at least two reasons. (1) Climate change damages are reduced, as the first term on the side of condition (3.12a) shows. (2) The world market prices of carbon energy will fall because of terms of trade effects.

3.2 Pareto-efficient strategies

Now, assume that regions cooperate and that international cooperation results in a Pareto-efficient solution of the global climate problem. Again we apply a two stage game. In stage 1 the North decides on investing into its own technology stock and/or on transferring technology to the South. In stage 2 regions cooperatively decide on mitigation. Since by assumption climate change does not directly affect utilities and regional welfare depends on conventional consumption only, the regions' consumption (see (2.3)) again is taken as proxy of regional welfare. Then for a Pareto-efficient allocation

$$[\Phi_N(e_N + e_S)F_N(Z_N, e_N) - g_N(s_N)] + [\Phi_S(e_N + e_S)F_S(Z_S, e_S) - g_S(s_S)]$$

has to be maximized subject to the market constraint (2.2). This gives the following first order conditions

(3.16) $$[\Phi_N'(e_N + e_S)F_N + \Phi_N(e_N + e_S)\frac{\partial F_N}{\partial e_N}] + \Phi_S'(e_N + e_S)F_S - p = 0,$$

(3.17) $$[\Phi_S'(e_N + e_S)F_S + \Phi_S(e_N + e_S)\frac{\partial F_S}{\partial e_S}] + \Phi_N'(e_N + e_S)F_N - p = 0.$$

These conditions immediately imply

(3.18) $$\Phi_N(e_N + e_S)\frac{\partial F_N}{\partial e_N} = \Phi_S(e_N + e_S)\frac{\partial F_S}{\partial e_S},$$

which means that the green marginal productivity of energy has to be equal across regions. This is in some contrast to the results reported in the literature (for example, see Chichilnisky and Heal, 1994), where it is typically argued that without income transfers the marginal costs of abatement will not be the same across all regions. It is, however, consistent with the results shown in Manne and Stephan (2005).

To provide the basis for further investigation let us take the total differential of condition (3.18). Since $\frac{\partial^2 F_n}{\partial e_n^2} = 0$ (see condition (2.1)), this gives

(3.19) $$\left[\Phi_N' \frac{\partial F_N}{\partial e_N} - \Phi_S' \frac{\partial F_S}{\partial e_S}\right][de_N + de_S] = \Phi_S \frac{\partial^2 F_S}{\partial e_S \partial Z_S} dZ_S - \Phi_N \frac{\partial^2 F_N}{\partial e_N \partial Z_N} dZ_N,$$

where dZ_n denotes the change of the technology stock of region *n = N,S*.

Note, the right hand side of condition (3.19) denotes, how a change in the regions' technology stocks affects the interregional differential in green marginal productivity of energy. In optimum green marginal productivity has to be identical across regions (see condition (3.18)). Therefore, if technology transfers force the regions' green marginal productivity of energy to differ, there must be some correction through a change in inputs of carbon energy. To see this, let us first concentrate on the case that technology is transferred from the North to the South only, i.e., $dZ_S > 0, dZ_N = 0$. Obviously, the effect, transferring technologies has on global emissions, depends on the sign of the first expression in brackets on the left side of equation (3.19). If

$$\left[\Phi_N' \frac{\partial F_N}{\partial e_N} - \Phi_S' \frac{\partial F_S}{\partial e_S}\right] < 0,$$

then transferring technologies to the South implies an reduction of global emissions. Or, since $\Phi_n' < 0, n = N, S$

(3.20) $$1 > \frac{\Phi_S' \frac{\partial F_S}{\partial e_S}}{\Phi_N' \frac{\partial F_N}{\partial e_N}}.$$

Now, under realistic assumptions one would not expect that condition (3.20) is satisfied for the following reasons: (1) Economies of the South typically consume less carbon energy than those in the North. Therefore the marginal productivity of energy in the South should be higher than in the North. (2) Due to their higher exposure marginal damages of global warming change are higher in the South than in the North. Therefore, the expression of the right side of condition (3.20) is expected to be bigger than 1, which contradicts condition (3.20).

One consequence is that the chronological ordering matters. Transferring technologies first and then deciding cooperatively on climate change mitigation does not imply higher levels of greenhouse gas abatement compared to a situation without technology transfers. What, however, if the North not only transfers technologies, but also invests in its own technology stocks such that the expression on the right hand side of condition (3.19) gets negative? Then a reduction of global greenhouse gas emission under full cooperation is observed, if

$$\left[\Phi_N' \frac{\partial F_N}{\partial e_N} - \Phi_S' \frac{\partial F_S}{\partial e_S}\right] > 0,$$

And hence

(3.20a) $$\frac{\frac{\partial F_N}{\partial e_N}}{\frac{\partial F_S}{\partial e_S}} < \frac{\Phi_S'}{\Phi_N'}.$$

This fits with reality at least as long as the marginal productivity of energy is lower in the North than in the South, but marginal damages are higher in the South than in the North.

4 Conclusions

Can technology transfer be a complement or a substitute for internationally coordinated climate policy? As our analysis reveals, neither nor. Even under optimistic assumptions rebound and leakage effects hinder a sustainable and welfare improving solution of the climate problem. What turns out being a suitable option both in terms of regional welfare and climate change mitigation is imposing binding emission targets in the South and transferring, as kind of compensation, energy-efficient technologies from the industrialized to the developing countries. However, this is not really a novelty and it is not good news in addition. It immediately raises a compliance and commitment problem. Why should the South contribute to greenhouse gas abatement, once the technologies are transferred? One idea could be that technologies are transferred only, once the South established a reliable climate change policy, for example through implementing a carbon tax. This implies that the chronological ordering of policy steps is reversed compared to the scenarios discussed today, for it requires that there will be some reliable commitment for greenhouse gas abatement, before technologies are transferred.

The last observation not only applies in case of uncoordinated, unilateral climate policies. It also applies if cooperative climate policies are considered. If technologies are transferred from North to South first, and Pareto-efficient climate abatement is determined second, the flow of emissions is higher compared to a situation where emission targets are negotiated first and technologies are transferred second. This seriously challenges the idea that North-to-South technology transfer might be an isolated option. Technology transfer can be counterproductive unless countries face binding emission constraints, and hence should be part of a broader policy package. For given their need for continued economic growth, developing countries are unlikely to agree on constraining emissions without compensation from the developed countries. Technology transfer provides such form of compensation (see Popp, 2009), however.

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Appendix

Section 3.1.1

Taking the total differential of condition (3.1) as well as of the market condition (2.2) leads to the following system of linear equations

$$\begin{pmatrix} (S_N' + S_S') & -1 \\ -1 & \left(\Phi_S'' F_S + 2\Phi_S' \frac{\partial F_S}{\partial e_S}\right) \end{pmatrix} \begin{pmatrix} dp \\ de_S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\left(\Phi_S'' F_S + \Phi_S' \frac{\partial F_S}{\partial e_S}\right) & -\left(\Phi_S' \frac{\partial F_S}{\partial Z_S} + \Phi_S \frac{\partial^2 F_S}{\partial e_S \partial Z_S}\right) \end{pmatrix} \begin{pmatrix} de_N \\ dZ_S \end{pmatrix}.$$

Multiplying the second row with $\left(\Phi_S'' F_S + 2\Phi_S' \frac{\partial F_S}{\partial e_S}\right)^{-1}$ gives (3.7).

Section 3.1.2

Taking the total differential of condition (3.1) gives

$$(\Phi_n'' F_n + 2\Phi_n' \frac{\partial F_n}{\partial e_n}) de_n + (\Phi_n'' F_n + \Phi_n' \frac{\partial F_n}{\partial e_n}) de_{-n} + \left(\Phi_n' \frac{\partial F_n}{\partial Z_n} + \Phi_n \frac{\partial^2 F_n}{\partial e_n \partial Z_n}\right) dZ_n = dp.$$

Assume that $dZ_N = 0$ and that de_S is given

$$\text{(A.1)} \quad \begin{pmatrix} (S_N' + S_S') & -1 & 0 \\ -1 & \Phi_N'' F_N + 2\Phi_N' \frac{\partial F_N}{\partial e_N} & 0 \\ -1 & \Phi_S'' F_S + \Phi_S' \frac{\partial F_S}{\partial e_S} & \Phi_S' \frac{\partial F_S}{\partial Z_S} + \Phi_S \frac{\partial^2 F_S}{\partial e_S \partial Z_S} \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ dZ_S \end{pmatrix} = \begin{pmatrix} 1 \\ -[\Phi_N'' F_N + \Phi_N' \frac{\partial F_N}{\partial e_N}] \\ -[\Phi_S'' F_S + 2\Phi_S' \frac{\partial F_S}{\partial e_S}] \end{pmatrix} de_S$$

By multiplying the second row with $(\Phi_N'' F_N + 2\Phi_N' \frac{\partial F_N}{\partial e_N})^{-1}$ and the third one with $(\Phi_S'' F_S + 2\Phi_S' \frac{\partial F_S}{\partial e_S})^{-1}$ gives

(A.1.1) $$\begin{pmatrix} (S_N' + S_S') & -1 & 0 \\ -\frac{\partial e_N}{\partial p} & 1 & 0 \\ -\frac{\partial e_S}{\partial p} & 1 & -\frac{\partial e_S}{\partial Z_S} \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ dZ_S \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{\partial e_N}{\partial e_s} \\ \frac{\partial e_S}{\partial e_N} \end{pmatrix} de_S$$

For applying Cramer's rule, let us calculate the determinante of the above matrix, which is $det\bar{A} = -\frac{\partial e_S}{\partial Z_S}(S_N' + S_S' - \frac{\partial e_N}{\partial p}) < 0$.

$$dp = -\frac{\frac{\partial e_S}{\partial Z_S}\left(1+\frac{\partial e_N}{\partial e_S}\right)}{det\bar{A}} de_S = \frac{\left(1+\frac{\partial e_N}{\partial e_S}\right)}{S_N'+S_S'-\frac{\partial e_N}{\partial p}} de_S,$$

$$de_N = \frac{-\frac{\partial e_S}{\partial Z_S}\left((S_N'+S_S')\frac{\partial e_N}{\partial e_S}+\frac{\partial e_N}{\partial p}\right)}{det\bar{A}} de_S = \frac{\frac{\partial e_N}{\partial p}+(S_N'+S_S')\frac{\partial e_N}{\partial e_S}}{S_N'+S_S'-\frac{\partial e_N}{\partial p}} de_S$$

$$dZ_S = \frac{\frac{\partial e_S}{\partial e_N}\left((S_N'+S_S')-\frac{\partial e_N}{\partial p}\right)-\frac{\partial e_N}{\partial p}}{det\bar{A}} de_S - \frac{\frac{\partial e_N}{\partial e_S}\left((S_N'+S_S')-\frac{\partial e_S}{\partial p}\right)-\frac{\partial e_S}{\partial p}}{det\bar{A}} de_S.$$