Environ Resource Econ (2015) 62:791–809
DOI 10.1007/s10640-014-9818-4

Global Warming, Technological Change and Trade in Carbon Energy: Challenge or Threat?

Gunter Stephan · Georg Müller-Fürstenberger

Accepted: 4 August 2014 / Published online: 17 August 2014

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 two possible states of the world are discussed: one, where more energy efficient technologies are transferred unconditionally from the North to the South, and where regions do not cooperate in the solution of the global climate problem but unilaterally decide on climate policies and technology transfers; one, where the North-to-South technology transfer is tied to the requirement that the South in some way contributes to the solution of the global climate problem. Rebound and leakage effects hinder a sustainable and welfare improving solution of the climate problem.

Keywords Global warming · Climate change · Technological change · Technology transfer · Trade in carbon energy · Post-Kyoto-policy regimes

JEL Classification C68 · D58 · F18 · Q56 · Q54

Financial support by the Swiss National Center of Competence in Research on Climate (NCCR Climate) as well as the Swiss National Center of Competence in Research on Trade Regulations (NCCR Trade) funded by the Swiss National Science Foundation (SNF) is gratefully acknowledged. This paper was written during Stephan's research stay at the DIW, Berlin. Helpful comments have been provided by Benjamin Hecker as well as by two anonymous referees. However, the usual disclaimer applies.

G. Stephan (✉)
Department of Economics, Oeschger Centre of Climate Change Research (OCCR), Universität Bern, Bern, Switzerland
e-mail: gunter.stephan@vwi.unibe.ch

G. Stephan
DIW, Berlin, Germany

G. Müller-Fürstenberger
Department of Economics, Universität Trier, Trier, Germany

1 Introduction

The 2012 United Nations Climate Change Conference held in Doha, Qatar, ended with the agreement that the Kyoto-Protocol is extended until a new international agreement will become effective in 2020. This once again directed attention to the role, which technology development and technology transfer can play in combating climate change. One reason is that technology transfer can be achieved through bilateral arrangements without the need of a framework convention. This is of particular importance as long as the fastest-growing economies of Asia and Latin America are free of obligations to curb greenhouse gas emissions. A second reason is that technological change is at core in fighting climate change. Any stabilization of the atmospheric carbon concentration below catastrophic levels requires to eliminate carbon emissions almost completely within the next century (see McCarthy et al. 2001). The most effective way to do this is to develop and to use climate-friendly technologies. These could include improvements in energy efficiency, advanced technologies for generating electricity or carbon capturing and sequestration (CCS).

Today, the potential for inventing more energy-efficient and climate-related technologies is primarily concentrated in the industrialized countries. However, the need for such technologies is most urgent in the developing world. According to World Bank statistics (see World Bank 2013), the carbon intensity (measured in kg of CO2 per 2005 PPP$ of GDP) is significantly lower in high income countries than in low to middle income countries. Furthermore, the Energy Information Administration (2011) projects that by 2035 carbon emissions of non-OECD countries will exceed those of the OECD members by more than 100 %, while technological innovations will still occur in only a few, highly industrialized countries. Not surprisingly, a large number of both scientific and political commentaries advocate the development of new technologies and argue that the transfer of such technologies to developing countries must be a central element of any climate protection policy.

In a study, which covers the period from 1998 to 2003 and uses patent counts to measure both the output and transfer of technologies, Dechezlepretre et al. (2011) found that the majority of technology transfers is between the developed countries. North-to-South transfers account for less than 25 %, while South-to-South transfers are almost nonexistent. 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? How do the implementation and the transfer of more energy efficient technologies affect the global market for carbon energy and vice versa? And, under which circumstances does the North have an incentive at all for transferring advanced 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.[1]

For more than 20 years, the economic literature discusses how technology transfer can be helpful in avoiding the adverse effects of global climate change (for an overview see Popp 2011). Some papers take trade aspects into account (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; Ohta and Nakagawa 2008). Lee (2001) for example discloses such a paradox in the sense that, despite of the transfer, the industrialized donor gains economic welfare while

---

[1] 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) and Buob and Stephan (2013).

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). To explain this with an example suppose for a moment that the developing countries were net exporters of carbon energy and that transferring more efficient technologies would lead to a reduction of global demand for carbon energy (which it must not, as we will see below). Then world market prices of carbon energy would fall, from which welfare losses in the recipients' world and welfare gains in the donors' countries could result.

A part of the rich literature on the provision of public goods also discusses the issue of technology transfer and typically employs a game-theory setting where trade issues are neglected. For example Buchholz and Konrad (1994) show that if countries with an inferior technology adopt a more advanced one, the quality of the environment nonetheless might deteriorate. Stranlund (1996) demonstrates that both the environmental quality and the welfare of the donors will rise if the level of technology transfers was fixed, before countries non-cooperatively determine their optimal abatement activities. Golombek and Hoel (2011) discuss international cooperation on technology development as an alternative to international cooperation on emission reductions. They argue that because of technology spillovers each country should invest into new technologies beyond levels, which are optimal in the non-cooperative case. Finally, Helm and Pichler (2011) present evidence that in case of international permit trading subsidizing technology transfers will lead to a reduction of international permit prices, from which the industrialized countries can profit if they are permit buyers.

A third strand of literature uses numerical simulation models for analyzing qualitatively and quantitatively the effects of technology transfers. Much of this literature is based on the work of Yang (1999), Popp (2004) or Nordhaus and Yang (2006) and applies some variant of the RICE model of integrated assessment of global climate change.[2] Mostly the results sound encouraging. Recently, Aronsson et al. (2010) showed that if the countries of the South are free from obligations to curb 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 studies reveals that carbon energy is not an input into production and that 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 the North might be motivated to transfer technologies even if transfer costs are non-negligible.

Technology transfer, however, is not only a mean for lowering abatement costs. Technology transfer and innovation 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 % (see Dechezlepretre et al. 2011). The majority of transfers relate to patents on more energy efficient technologies. This motivates a first point of departure from the existing literature on technology transfer 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 raise greenhouse gas emissions (see Brännlund et al. 2007). The intuition is that improvements in energy efficiency create an income effect through which demand for energy is stimulated. Or to phrase it differently, efficiency gains wipe out the emission reductions, and hence, a "rebound effect" occurs.

---

[2] For an exception see for example Cian et al. (2012), who apply the WITCH model.

Most of the literature on technological change and the provision of public goods, which is relevant in our context, do 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 on 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.[3] 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 could generate terms-of-trade effects, which let the unconstraint region import more carbon energy and hence emit more than it would do otherwise (for a discussion, see Burniaux and Oliveira-Martins 2000).

The rest of the paper is organized as follows. Section 2 presents the 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 technologies are transferred unconditionally from the North to the South, and where regions do not cooperate in the solution of the global climate problem but unilaterally decide on climate policies and technology transfers; one, where the North-to-South technology transfer is tied to the requirement that the South in some way contributes to the solution of the global climate problem. Section 4 concludes.

2 A Simple Model

To fix ideas, let the world be divided into two regions. For vividness they are 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.

For each region outputs are aggregated into a single numeraire good, which can be consumed domestically and can be used to cover costs of energy supply. To keep considerations as simple as possible, technological knowledge and carbon energy are the only inputs into regional production. Formally this implies that for each region $n = N, S$ gross domestic production is characterized by the function $F_n(Z_n, e_n)$, where the region's energy input e_n is measured in carbon equivalents to energy consumption. This directly governs 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 means in particular that new technologies can increase the energy efficiency and/or might reduce the carbon intensity of domestic production. Note that increased energy efficiency here is understood as the possibility to produce the same output with lower energy inputs but without increasing the inputs of other factors of production (see Golombek and Hoel 2011): For, if increased energy efficiency could be achieved through using more of other inputs, this would be a substitution effect only. This, by the way, is a justification why we keep our modeling framework deliberately simple.

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

---

[3] 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.

(1) Once installed in a region, technological knowledge is a non-rival input into regional production and can be applied as often as desired.[4]

Given that regional production is linear homogenous in energy this implies[5]

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

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

That means, each region has the ability to capture all benefits derived from more efficient technologies and can exclude other regions from using that technology. This in turn implies that sharing technological knowledge entails the policy decision to transfer technologies. Note here that the stock of technology Z_N is given and not subject to endogenous change. Transferring technology simply means that Z_S gets closer to Z_N.

According to the Intergovernmental Panel on Climate Change (IPCC) technology transfers include the diffusion of technological knowledge as well as technology cooperation across and within countries (see Peterson 2008). On one hand this requires learning to understand, to utilize and to replicate the new technologies. On the other hand it requires the ability to choose and to adapt technologies to the local conditions (see Metz 2007). As such technology transfer occurs neither automatically nor costless. However, since we are interested in the strategic interaction between mitigation and the transfer of more energy efficient technologies, for the sake of simplicity we neglect the issue of costs of technology transfers. Furthermore let us neglect the issue of developing new technologies. Instead, we assume throughout this paper that the North always owns a stock of more energy efficient technologies, i.e. $Z_N > Z_S$, which can be transferred free of costs to the South.

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

$$s_N + s_S - e_N - e_S = 0. \tag{2.2}$$

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 one hand there are impacts, which can be directly measured in terms of output losses. For example, in 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.

This paper concentrates on market damages of climate change, or to phrase it differently, the impacts of climate change materialize in losses of regional gross production of the composite good.[6] Therefore, let $\Phi_n\left(e_N + e_S\right)$, with $\Phi_n' < 0$ and $\Phi_n'' < 0$, denote the regional

---

[4] For example, once the laws of thermodynamics have been discovered, they could be applied as often as desired. This discriminates technological knowledge from human capital, where knowledge is inherently tied to a person, hence can be used only if that person is present.

[5] As indicated by one of the referees, notation could be simplified by using $F_n\left(Z_n, e_n\right) = \alpha_n(Z_n)e_n$.

[6] Sectors differ with respect to their vulnerability to climate change. Some sectors such as agriculture, fishery and forestry are highly sensitive. Other sectors such as telecommunication or industrial manufacturing remain almost unaffected by climate change. As common in the integrated assessment literature (see Nordhaus and Boyer 2000), we aggregate sectoral outputs of a given region into a single composite good and express the effects of climate change on the production in percentage output losses.

climate damage factor, which is a function of global emissions and measures the fraction of conventional 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

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

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 more energy efficient technologies are transferred unconditionally from the North to the South, and one, where the North-to-South technology transfer is tied to the requirement that the South in some way contributes to the solution of the global climate problem (see Table 1 for a summary of the main characteristics of the four scenarios under consideration).

In case of unconditional transfers we discuss two different scenarios. The first one very much reminds of a fallback into a pre-Kyoto world. It is based upon the assumption that the North unconditionally transfers more energy efficient technologies to South and that both regions then independently determinate their abatement levels. The second scenario, which is called Kyoto-forever, reflects the situation that the Kyoto protocol is extended and that the North combines tightening its own emission targets, as proposed by the European Union, with technology transfers to the South.

If the North-to-South transfer is conditional in the sense that technologies are transferred only if the South engages in climate change mitigation, two further scenarios are considered. The first one is called Kyoto-reversed. It reflects a state of the world where the South no longer is free of obligations to curb greenhouse gas emissions. In particular, not only technologies but also the duty of greenhouse gas abatement is shifted from North to South. Obviously this is not a very realistic scenario. It is added for clarifying the effects of policy interventions based on technology transfers. The second scenario among the "conditional" ones is called cooperative. It is based on the assumption that once more efficient technologies are transferred, both regions fully cooperate and decide on Pareto-efficient mitigation policies.

In any of afore mentioned scenarios a 2-stage game is employed. In the two scenarios, where technologies are transferred unconditionally as well as in the Kyoto-reversed scenario regions act as if they were Nash players who unilaterally decide on climate policies and technology transfers. As usual, sub-game perfect equilibriums are obtained through backward induction. That means, given the decisions of the first stage, regions independently maximize welfare in the second one. Therefore, before analyzing the different scenarios separately, let us consider some properties, which generally follow, if regions maximize welfare without reflecting that their decision will affect 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. Thus in case of non-cooperation regions independently solve the problem

Table 1 Main characteristics of scenarios

	North	South
Unconditional transfers		
Pre-Kyoto		
Stage 1	North exogenously decides on technology transfer	
Stage 2	Both regions non-cooperatively maximize welfare	
Kyoto forever		
Stage 1	North exogenously decides on emission reductions and technology transfer	
Stage 2	Both regions non-cooperatively maximize welfare	
Conditional transfers		
Kyoto reversed		
Stage 1	North exogenously decides on technology transfer	South exogenously decides on emission reductions
Stage 2	Both regions non-cooperatively maximize welfare	
Post-Kyoto Cooperation		
Stage 1	North exogenously decides on technology transfer	
Stage 2	Both regions cooperatively maximize welfare	

Recall that the focus of the analysis is on answering the question: under which circumstances is it rational from an economic perspective to transfer technologies from North to the South. Therefore, we are not looking for optimal levels of transfers or abatement in Stage 1. Instead these are set arbitrary

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

Necessary conditions for an interior solution are

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

$$-\,g_n'\,(s_n)+p=0. \tag{3.2}$$

Condition (3.2) indicates: (1) regional supply of carbon energy $s_n(p)$ is a strictly increasing function of price p, (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 opposing effects. On 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

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

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 damage $\Phi_n' F_n$. 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 is the leakage effect and the last indicates that there might be a rebound effect.

Because of the assumptions imposed on the damage function Φ_n the price effect is negative,

$$\frac{\partial e_n}{\partial p} = \frac{1}{\Phi''_n F_n + 2\Phi'_n \frac{\partial F_n}{\partial e_n}} < 0. \tag{3.4}$$

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

$$\frac{\partial e_n}{\partial e_{-n}} = -\frac{\Phi''_n F_n + \Phi'_n \frac{\partial F_n}{\partial e_n}}{\Phi''_n F_n + 2\Phi'_n \frac{\partial F_n}{\partial e_n}} = -\frac{\Phi''_n e_n + \Phi'_n}{\Phi''_n e_n + 2\Phi'_n}, \tag{3.5}$$

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

$$\frac{\partial e_n}{\partial Z_n} = -\frac{\Phi'_n \frac{\partial F_n}{\partial Z_n} + \Phi_\mathrm{n} \frac{\partial^2 F_n}{\partial e_n \partial Z_n}}{\Phi''_n F_n + 2\Phi'_n \frac{\partial F_n}{\partial e_n}} = -\frac{\frac{\partial^2 F_n}{\partial e_n \partial Z_n}}{\frac{\partial F_n}{\partial e_n}} \frac{(\Phi'_n e_n + \Phi_\mathrm{n})}{\Phi''_n e_n + 2\Phi'_n} > 0 \tag{3.6}$$

is positive as follows from condition (3.3). Hence, although the energy efficiency[7] increases, more energy will be used as input into production and a rebound effect is observed.

3.1 Unconditional North-to-South Technology Transfers

3.1.1 Transfers in a Pre-Kyoto World

As mentioned above the first scenario is based on the assumption that in stage 1 the North decides to transfer unconditionally technologies to the South, while in stage 2 both regions independently determine their optimal levels of greenhouse gas emissions. For analyzing the effects of an unconditional North-to-South technology transfer, i.e., $dZ_S > 0$, on prices and emissions, let us take the total differential of condition (3.1) as well as of the market condition (2.2). After some manipulations this leads to the following system of linear equations (see "Appendix")

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

---

[7] Note that $D\left(\frac{F_n(Z_n, e_n)}{e_n}\right) = \frac{\frac{\partial F_n}{\partial e_n} e_n - F_n}{e_n^2} de_n + \frac{\frac{\partial F_n}{\partial Z_n}}{e_n^2} dZ_n > 0.$

Let $det A$ denote the determinate of the above matrix, which is positive as is shown in the "Appendix". By applying Cramer's rule we get from (3.7) as well as conditions (3.4), (3.5), (3.6)

$$\frac{dp}{dZ_S} = \frac{\frac{\partial e_S}{\partial Z_S}\left(1+\frac{\partial e_N}{\partial e_S}\right)}{det A} > 0. \tag{3.8}$$

Obviously, the world market price of carbon energy is driven by a raising demand for energy in the South caused by a rebound effect (see condition (3.6)). This price increase, however, is slightly dampened, since the North counteracts by reducing its own inputs of carbon energy (see condition (3.5)). In other words, there is what might be called a combination of rebound effects and an "inverse" leakage effect where the rebound effect, however, dominates.

That the South indeed extends its consumption of carbon energy and hence its greenhouse gas emission, whereas the North reduces its own carbon emissions in response to the rebound effect caused by transferring more energy efficient technologies to the South, becomes obvious if we consider

$$\frac{de_S}{dZ_S} = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S) - \frac{\partial e_N}{\partial p}\right)}{det A} > 0, \tag{3.9}$$

$$\frac{de_N}{dZ_S} = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S)\frac{\partial e_N}{\partial e_S} + \frac{\partial e_N}{\partial p}\right)}{det A} < 0. \tag{3.10}$$

The positive sign in (3.9) and the negative sign in (3.10) immediately follow from conditions (3.4) to (3.6). Combining them gives

$$\frac{de_N + de_S}{dZ_S} = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S)(1+\frac{\partial e_N}{\partial e_S})\right)}{det A} > 0,$$

which by applying condition (3.8) implies

$$\frac{de_N + de_S}{dZ_S} = (s'_N + s'_S)\frac{dp}{dZ_S} = \frac{d(s'_N + s'_S)}{dZ_S}.$$

In other words, unconditional North-to-South technology transfer leads to an increase of global carbon emission, which is driven by an increase in supply of carbon energy and which corresponds to an increase of the world market price of carbon energy.

Now, let us turn to the first stage of the game and let us ask the question: Under which condition would it be economically rational to unconditionally transfer more energy efficient technologies from North to South? Differentiating condition (2.3) implies

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

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

$$\frac{dc_N}{dZ_S} = \Phi'_N F_N \frac{de_S}{dZ_S} + (s_N - e_N)\frac{dp}{dZ_S}, \tag{3.11}$$

$$\frac{dc_S}{dZ_S} = \Phi'_S F_S \frac{de_N}{dZ_S} + \Phi_S \frac{\partial F_S}{\partial Z_S} + (s_S - e_S)\frac{dp}{dZ_S}. \tag{3.12}$$

Obviously, the North could profit from such a policy only if it is a net-exporter of carbon energy and if the increase in profits from net exports due to raising world market prices of carbon energy would overcompensate the welfare losses caused by raising market damages of global climate change. In any other case the North has no economic incentive to transfer technologies unconditionally to the South as condition (3.11) indicates. The South, however, can profit; in particular in case if the South is a net-exporter of carbon energy (see condition (3.12)). As such the overall message is clear. From an unconditional transfer of more energy efficient technologies neither the climate nor the donator will profit. Transferring more energy efficient technologies creates a rebound effect in the South, which is high enough to let the world-wide consumption of carbon energy grow. This happens despite of the fact that due to rising energy prices the North reduces its own consumption. Or to phrase it more provocatively, unconditional technology transfers are more or less nothing else than wealth transfers from the North to the South.

3.1.2 Kyoto-Forever

The next scenario, which is called Kyoto-forever, combines two elements of international climate policies: (1) a significant reduction of greenhouse gas emissions in Annex I countries as already announced by the European Union, and (2), transfers of advanced technologies from the developed to the developing world as originally foreseen in the Kyoto-Protocol and reinforced by the Bali Action Plan (see Marcellino and Gerstetter 2010).[8] In other words, the Kyoto-forever scenario assumes that in stage 1 the North simultaneously decides on own mitigation and technology transfers. Therefore, at the 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. Then condition (3.1) together with the market clearance condition (2.2) determine the following system of linear equations, which characterizes the South's decision problem in stage 2 (see "Appendix")

$$\begin{pmatrix} (s'_N + s'_S) & -1 \\ -\frac{\partial e_S}{\partial p} & 1 \end{pmatrix} \begin{pmatrix} dp \\ de_S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{\partial e_S}{\partial e_N} & \frac{\partial e_S}{\partial Z_S} \end{pmatrix} \begin{pmatrix} de_N \\ dZ_S \end{pmatrix}. \tag{3.13}$$

By using Cramer's rule we get

$$dp = \frac{1 + \frac{\partial e_S}{\partial e_N}}{s'_N + s'_S - \frac{\partial e_S}{\partial p}} de_N + \frac{\frac{\partial e_S}{\partial Z_S}}{s'_N + s'_S - \frac{\partial e_S}{\partial p}} dZ_S, \tag{3.14}$$

$$de_S = \frac{\frac{\partial e_S}{\partial p} + \left(s'_N + s'_S\right) \frac{\partial e_S}{\partial e_N}}{s'_N + s'_S - \frac{\partial e_S}{\partial p}} de_N + \frac{\left(s'_N + s'_S\right) \frac{\partial e_S}{\partial Z_S}}{s'_N + s'_S - \frac{\partial e_S}{\partial p}} dZ_S. \tag{3.15}$$

As condition (3.14) 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, which the changing energy consumption in the North has on prices. Since $0 > \frac{\partial e_S}{\partial e_N} > -1$, net impacts are positive and world market prices ceteris paribus will fall, if the North decides to reduce its inputs of carbon energy. (2) The numerator of the second term on the right

---

[8] Under the Convention, the developed country parties and other developed parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other parties, particularly to developing countries to enable them to implement the provisions of the Convention (Article 4.5 UNFCCC).

side reflects that transferring technologies to the South will stimulate the South's demand of carbon energy. Thus the world market price of carbon energy ceteris paribus will rise.

This indicates that we will observe both a leakage and a rebound effect. This becomes more obvious if we consider condition (3.15). As the second term on the right hand side shows, increasing the energy efficiency in the South through technology transfer will stimulate the demand for carbon energy, hence this will lead to higher carbon emissions in the South. This is what the literature calls a rebound effect.

Recalculation of the first term of Eq. (3.15) gives

$$0 > -\frac{\left(s_N' + s_S'\right)\left(-\frac{\partial e_S}{\partial e_N}\right) - \frac{\partial e_S}{\partial p}}{\left(s_N' + s_S'\right) - \frac{\partial e_S}{\partial p}} > -\frac{\left(s_N' + s_S'\right) - \frac{\partial e_S}{\partial p}}{\left(s_N' + s_S'\right) - \frac{\partial e_S}{\partial p}} = -1,$$

which implies leakage. However, the leakage effect does not fully compensate the reduction of emissions, which 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-forever could turn out to be a bad policy, both for the global climate as well as for 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 (3.15)). 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-forever Pareto improving?

First, suppose that $de_S + de_N \leq 0$. This requires (see (3.15))

$$(s_N' + s_S')\left(1 + \frac{\partial e_S}{\partial e_N}\right) de_N + \left(s_N' + s_S'\right)\frac{\partial e_S}{\partial Z_S} dZ_S \leq 0,$$

hence

$$dZ_S \leq -\frac{1 + \frac{\partial e_S}{\partial e_N}}{\frac{\partial e_S}{\partial Z_S}} de_N. \tag{3.16}$$

Accordingly, 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 the leakage effect and the smaller the rebound effect, the more technology can be transferred to the South without increasing global greenhouse gas emissions.[9]

Note further, if $de_N < 0$, conditions (3.8) and (3.10) imply $dp \leq 0$. 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.

---

[9] 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 one hand and energy consumption as well as marginal damages on the other.

Next, let us discuss the second question from above. As in Sect. 3.1.1, condition (2.3) implies

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

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

Now suppose that technology transfers are low enough such that condition (3.16) 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 (3.16) is not satisfied, world market prices of carbon energy will rise and the South will only profit for sure if the North is net-importer and the South is net-exporter of carbon energy.

Under Kyoto-forever assumptions the North has for economic reasons almost no incentive to transfer technologies to the South. As condition (3.12a) 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 (3.16) is fulfilled and global emissions drop, condition (3.12a) implies

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

which is negative because of leakage (see (3.15)).

3.2 Conditional North-to-South Transfers

3.2.1 Kyoto-Reversed

Under Kyoto-reversed assumptions not only more energy efficient technologies but also part of the duty to reduce greenhouse gas emissions is shifted from Annex I to non-Annex I countries. This means that in the first stage the North decides to transfer technologies, while the South commits itself on climate mitigation. Hence, at the beginning of stage 2 technology transfers dZ_S as well as changes in the South's input of carbon energy de_S are given.[10] Therefore condition (3.1) together with the market clearance condition (2.2) after some manipulations now gives

$$\begin{pmatrix} (s'_N + s'_s) & -1 \\ -\frac{\partial e_N}{\partial p} & 1 \end{pmatrix} \begin{pmatrix} dp \\ de_N \end{pmatrix} = \begin{pmatrix} de_S \\ \frac{\partial e_N}{\partial e_S} de_S \end{pmatrix}. \tag{3.17}$$

By using Cramer's rule we get

$$dp = \frac{1 + \frac{\partial e_N}{\partial e_S}}{s'_N + s'_s - \frac{\partial e_N}{\partial p}} de_S. \tag{3.18}$$

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

Falling prices ceteris paribus stimulate rising demand for carbon energy in the North. Indeed, from (3.17) by applying Cramer's rule again we obtain

$$de_N = \frac{\frac{\partial e_N}{\partial p} + \left(s'_N + s'_s\right) \frac{\partial e_N}{\partial e_S}}{s'_N + s'_s - \frac{\partial e_N}{\partial p}} de_S. \tag{3.19}$$

---

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

This 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.

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

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

$$dc_N = \Phi_N' F_N de_S + (s_N - e_N)\, dp. \tag{3.12b}$$

If, as was supposed above, the North is a net importer of carbon energy and the South is a net exporter, the South nonetheless might profit, provided that the green marginal productivity of technologies as well as technology transfer are high enough. For $dc_S \geq 0$ only, if

$$\Phi_S \frac{\partial F_S}{\partial Z_S} dZ_S \geq -\Phi_S' F_S de_N - (s_S - e_S)\, dp.$$

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 (3.12b) shows. (2) The world market prices of carbon energy will fall because of terms of trade effects.

Some might argue that such scenario is not a valuable policy option. Concerns for fairness and equity can have significant influence on the negotiations of an international climate treaty. Since developing countries often view themselves as victims of the developed world's industrialization, these countries in particular might regard such a policy as unfair. As experiments show, offers are refused if perceived as unfair, even if doing so comes at significant personal cost. A closer look reveals that this could be the case. As condition (3.11b) indicates there is a high chance that the developing world could profit from technology transfers even if combined with the duty of domestic emission reductions. If technologies, which are not available in the recipients' countries, are transferred, industrialized countries, which have accepted emissions reduction targets, are allowed to get compensated credits. Seen from this perspective Kyoto-reversed is a kind of a Clean Development Mechanism (CDM).[11]

3.2.2 Post-Kyoto Cooperation

Now, assume that regions cooperate in climate change mitigation. To avoid misunderstandings, recall that this does not mean that international cooperation will result in Pareto-efficient strategies for both technology transfer and greenhouse gas abatement. Instead, we are looking for a situation where regions cooperatively determine their emission strategies once more efficient technologies have been transferred from North to South. In other words, we apply a two stage game. In stage 1 the North decides on transferring technology to the South, while 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 mitigation policy

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

---

[11] While technology transfer is not an explicit element of the CDM, it nevertheless offers the opportunity to transfer technologies to developing countries. Dechezlepretre et al. (2008) analyzed a sample of 644 registered projects and found that 43 % of projects involve technology transfer representing 84 % of the expected annual emission reductions.

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

$$\left[\Phi_N'\left(e_N+e_S\right)F_N+\Phi_N\left(e_N+e_S\right)\frac{\partial F_N}{\partial e_N}\right]+\Phi_S'\left(e_N+e_S\right)F_S-p=0, \quad (3.20)$$

$$\left[\Phi_S'\left(e_N+e_S\right)F_S+\Phi_S\left(e_N+e_S\right)\frac{\partial F_S}{\partial e_S}\right]+\Phi_N'\left(e_N+e_S\right)F_N-p=0, \quad (3.21)$$

which immediately imply

$$\Phi_N\left(e_N+e_S\right)\frac{\partial F_N}{\partial e_N}=\Phi_S\left(e_N+e_S\right)\frac{\partial F_S}{\partial e_S}. \quad (3.22)$$

This means that the green marginal productivity of energy has to be equal across regions. This contradicts the results reported for example by Chichilnisky and Heal (1994), who argue 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).

Condition (3.22) furthermore implies (see condition (2.1))

$$\frac{e_S}{e_N}=\frac{\Phi_N F_N}{\Phi_S F_S}, \qquad \text{hence}$$

$$\frac{\partial \frac{e_S}{e_N}}{\partial Z_S}=-\frac{e_S}{e_N}\frac{\frac{\partial F_S}{\partial Z_S}}{F_S}<0.$$

Therefore, the ratio $\frac{e_S}{e_N}$ does ceteris paribus not rise if more efficient technologies are transferred to the South. Does this imply that in case of cooperation in climate change mitigation North-to-South technology transfers stipulate additional greenhouse gas abatement? To answer this question, let us take the total differential of condition (3.22). Since $\frac{\partial^2 F_n}{\partial e_n^2}=0$ (see condition (2.1)), this gives

$$\left[\Phi_N'\frac{\partial F_N}{\partial e_N}-\Phi_S'\frac{\partial F_S}{\partial e_S}\right]\left[de_N+de_S\right]=\Phi_S\frac{\partial^2 F_S}{\partial e_S\partial Z_S}dZ_S-\Phi_N\frac{\partial^2 F_N}{\partial e_N\partial Z_N}dZ_N, \quad (3.23)$$

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

The right hand side of condition (3.23) shows 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 (3.22)). 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. Furthermore the effect of transferring technologies (i.e., $dZ_S>0, dZ_N=0$) on global emissions, depends on the sign of the first expression in brackets on the left side of Eq. (3.23). 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 a reduction of global emissions. Or, since $\Phi_n'<0, n=N,S$

$$1>\frac{\Phi_S'\frac{\partial F_S}{\partial e_S}}{\Phi_N'\frac{\partial F_N}{\partial e_N}}. \quad (3.24)$$

Now, under realistic assumptions one would not expect that condition (3.24) 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

Table 2 Summary of major results

	Effects on	North	South
Pre-Kyoto	World market price of energy	$dp > 0$	
	Regional emissions	$de_N < 0$	$de_S > 0$
	Global emissions	$de_N + de_S > 0$	
	Welfare	$dc_N < 0$ if North is net importer	$dc_S > 0$ if South is net-exporter
Kyoto forever	Price of energy	$dp \leq 0, if dZ_S \leq -\frac{1+\frac{\partial e_S}{\partial e_N}}{\frac{\partial e_S}{\partial Z_S}} de_N$	
	Regional emissions	$de_N < 0$ exogenously given	$de_S > 0$
	Global emissions	$de_N + de_S \leq 0, if dZ_S \leq -\frac{1+\frac{\partial e_S}{\partial e_N}}{\frac{\partial e_S}{\partial Z_S}} de_N$	
	Welfare	$dc_N < 0$	$dc_S > 0$
Kyoto reversed	Price of energy	$dp \leq 0$	
	Regional carbon emissions	$de_N > 0$	$de_S < 0$ exogenously given
	Global carbon emissions	$de_N + de_S < 0$	
	Welfare	$dc_N > 0$	$dc_S > 0, \quad if \Phi_S \frac{\partial F_S}{\partial Z_S} dZ_S \geq -\Phi'_S F_S de_N - (s_S - e_S)\, dp$
Post-Kyoto Cooperation	Global emissions	$de_N + de_S \leq 0$, if $1 > \frac{\Phi'_S \frac{\partial F_S}{\partial e_S}}{\Phi'_N \frac{\partial F_N}{\partial e_N}}$	

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 (3.24) is expected to be bigger than 1, which is in contradiction to condition (3.24). 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.

4 Conclusions

Can technology transfer be a complement or a substitute for an internationally coordinated climate policy?[12] As our analysis reveals, even under optimistic assumptions rebound and leakage effects hinder a welfare improving solution of the climate problem. Under the presently prevailing climate policy regime, which corresponds to a Kyoto-forever scenario, the North has for economic reasons almost no incentive to voluntarily transfer technologies to the South even at costs zero. Furthermore, global emissions will go down only if an upper limit on the North-to-South technology transfer is obeyed. Such limit 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. What turns out to be a suitable option both in terms of regional welfare and climate change mitigation is to impose binding emission targets in the South

---

[12] Table 2 summarizes the main findings of the analysis.

and transferring, as a 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 either. 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. Given their need for continued economic growth, developing countries are unlikely to agree on constraining emissions without compensation from the developed countries. Technology transfer could be such form of compensation (see Popp 2009).

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

$$\begin{pmatrix} (s'_N + s'_S) & -1 & -1 \\ -1 & \Phi''_N F_N + 2\Phi'_S \frac{\partial F_N}{\partial e_N} & \Phi''_N F_N + \Phi'_S \frac{\partial F_N}{\partial e_N} \\ -1 & \Phi''_S F_S + \Phi'_S \frac{\partial F_S}{\partial e_S} & \Phi''_s F_S + 2\Phi'_S \frac{\partial F_S}{\partial e_S} \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ de_S \end{pmatrix}$$
$$= \begin{pmatrix} 0 \\ 0 \\ -\left(\Phi'_S \frac{\partial F_S}{\partial Z_S} + \Phi_\mathrm{S} \frac{\partial^2 F_S}{\partial e_S \partial Z_S} \right) \end{pmatrix} dZ_S$$

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

$$\begin{pmatrix} (s'_N + s'_S) & -1 & -1 \\ -\frac{\partial e_N}{\partial p} & 1 & -\frac{\partial e_N}{\partial e_s} \\ -\frac{\partial e_S}{\partial p} & -\frac{\partial e_S}{\partial e_N} & 1 \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ de_S \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \frac{\partial e_S}{\partial Z_S} \end{pmatrix} dZ_S$$

For applying Cramer's rule, let us calculate the determinant of the above matrix $det A = (s'_N + s'_S)\left(1 - \frac{\partial e_N}{\partial e_s}\frac{\partial e_S}{\partial e_N}\right) - \frac{\partial e_N}{\partial p}\left(1 + \frac{\partial e_S}{\partial e_N}\right) - \frac{\partial e_S}{\partial p}\left(1 + \frac{\partial e_N}{\partial e_s}\right) > 0$. The positive sign directly follows from condition (3.4) and (3.5). Then Cramer's rule implies

$$dp = \frac{\frac{\partial e_S}{\partial Z_S}\left(1 + \frac{\partial e_N}{\partial e_S}\right)}{\det A} dZ_S > 0,$$

$$de_N = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S)\frac{\partial e_N}{\partial e_S} + \frac{\partial e_N}{\partial p}\right)}{\det A} dZ_S < 0,$$

$$de_S = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S) - \frac{\partial e_N}{\partial p}\right)}{\det A} dZ_S > 0.$$

Hence

$$\frac{de_N + de_S}{dZ_S} = \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S)\frac{\partial e_N}{\partial e_S} + \frac{\partial e_N}{\partial p}\right)}{\det A} + \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S) - \frac{\partial e_N}{\partial p}\right)}{\det A}$$

$$= \frac{\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_S)(1 + \frac{\partial e_N}{\partial e_S})\right)}{\det A} > 0.$$

Section 3.1.2

Taking the total differential of condition (3.1) as well as of the market condition (2.2) leads to the 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 3.2.1

Taking the total differential of condition (3.1) gives

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

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

$$\begin{pmatrix} (s'_N + s'_S) & -1 & 0 \\ -1 & \Phi''_N F_N + 2\Phi'_N \frac{\partial F_N}{\partial e_N} & 0 \\ -1 & \Phi''_S F_S + \Phi'_S \frac{\partial F_S}{\partial e_S} & \Phi'_S \frac{\partial F_S}{\partial Z_S} + \Phi_S \frac{\partial^2 F_S}{\partial e_S \partial Z_S} \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ dZ_S \end{pmatrix}$$

$$= \begin{pmatrix} 1 \\ -[\Phi''_N F_N + \Phi'_N \frac{\partial F_N}{\partial e_N}] \\ -[\Phi''_S F_S + 2\Phi'_S \frac{\partial F_S}{\partial e_S}] \end{pmatrix} de_S \qquad (4.1)$$

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

$$\begin{pmatrix} (s'_N + s'_S) & -1 & 0 \\ -\frac{\partial e_N}{\partial p} & 1 & 0 \\ -\frac{\partial e_S}{\partial p} & 1 & -\frac{\partial e_S}{\partial Z_S} \end{pmatrix} \begin{pmatrix} dp \\ de_N \\ dZ_S \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{\partial e_N}{\partial e_s} \\ \frac{\partial e_S}{\partial e_N} \end{pmatrix} de_S \tag{4.2}$$

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

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

$$de_N = \frac{-\frac{\partial e_S}{\partial Z_S}\left((s'_N + s'_s)\frac{\partial e_N}{\partial e_S} + \frac{\partial e_N}{\partial p}\right)}{det\bar{A}} de_S = \frac{\frac{\partial e_N}{\partial p} + \left(s'_N + s'_s\right)\frac{\partial e_N}{\partial e_S}}{s'_N + sS'_S - \frac{\partial e_N}{\partial p}} de_S$$

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

References

Aronsson T, Backlund K, Sahlen L (2010) Technology transfers and the clean development mechanism in a North–South general equilibrium model. Resour Energy Econ 32:292–309

Bhagwati JN, Brecher RA, Hatta T (1983) The generalized theory of transfers and welfare: bilateral welfare in a multilateral world. Am Econ Rev 73:606–618

Barrett S (2006) Climate treaties and 'breakthrough' technologies. Am Econ Rev 96:22–25

Brännlund R, Ghalwash T, Nordström J (2007) Increased energy efficiency and the rebound effect: effects on consumption and emissions. Energy Econ 29:1–17

Buchholz W, Konrad KA (1994) Global environmental problems and the strategic choice of technology. J Econ 60:299–321

Buob S, Stephan G (2013) On the incentive compatibility of funding adaptation. Climate Change Econ 4:1–18

Burniaux JM, Oliveira-Martins J (2000) Carbon Emission leakages: a general equilibrium view. OECD Working Paper 242, OECD, Paris

Chichilnisky G, Heal G (1994) Who should abate carbon emissions. An international viewpoint. Econ Lett 44:443–449

Copeland B, Taylor MS (2004) Trade, spatial separation and the environment. J Int Econ 47:137–168

Dechezlepretre A, Glachant M, Meniere Y (2008) The clean development mechanism and the international diffusion of technologies: an empirical study. Energy Policy 36:1273–1281

Dechezlepretre A, Glachant M, Hascic I, Johnstone N, Meniere Y (2011) Invention and transfer of climate change–mitigation technologies: a global analysis. Rev Environ Econ Policy 5:109–130

De Cian E, Bosetti V, Tavoni M (2012) Technology innovation and the diffusion in "less than ideal" climate policies: an assessment with the WITCH model. Clim Change 114:121–142

Energy Information Administration (2011) International Energy Outlook 2011. Release September 19, 2011. U.S. Department of Energy, Washington, DC

Gillingham K, Newell R, Pizer W (2007) Modeling Endogenous technological change for climate policy analysis. RFF Discussion Paper 07–14, Resources for the Future, Washington DC

Golombek R, Hoel M (2011) International cooperation on climate-friendly technologies. Environ Res Econ 49:473–490

Helm C, Pichler S (2011) Climate policy with technology transfers and permit trading. Oldenburg Discussion Papers in Economics V-341-111, Oldenburg

Lee TY (2001) Effects of technology transfers on the provision of public goods. Environ Res Econ 18:193–218

Manne A, Stephan G (2005) Global climate change and the equity–efficiency puzzle. Energy 30:2525–2536

Marcellino D, Gerstetter C (2010) Technology transfer in the international climate negotiations: assessment of proposals and discussion of open questions. Ecologic Institute, Washington, DC

McCarthy J, Canziani O, Leary N, Dokken D, White K (2001) Climate Change 2001: impacts, adaptation and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Metz B (2007) Climate Change 2007: mitigation of climate change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Nordhaus W, Boyer J (2000) Warming the world. MIT Press, Cambridge

Nordhaus W, Yang Z (2006) Magnitude and direction of technological transfers for mitigating GHG emissions. Energy Econ 28:730–741

Nordhaus W (2009) The economics of an integrated world oil market. In: Address prepared for annual conference of energy information agency, 2009, and the 2009 meeting of international energy workshop

Ohta H, Nakagawa H (2008) On the technology transfer paradox and the worsening terms of trade paradox. Asia-Pac J Account Econ 15:41–54

Peterson S (2008) Greenhouse gas mitigation in developing countries through technology transfer? A survey of empirical evidence. Mitig Adapt Strat Glob Change 13:283–305

Popp D (2004) ENTICE: endogenous technological change in the DICE model of global warming. J Environ Econ Manag 48:742–768

Popp D (2009) A perspective paper on technology transfer as a response to climate change. Copenhagen Consensus Center, August 28, 2009

Popp D (2011) International technology transfer for climate policy. Rev Environ Econ Policy 5:131–152

Stranlund JK (1996) On the strategic potential of technological aid in international environmental relation. J Econ 64:1–22

Takarada Y (2005) Transboundary pollution and the welfare effects of technology transfers. J Econ 85:251–275

World Bank (2013) World Development Indicators: CO2 Emissions (kg per 2005 PPP$ of GDP)

Yang Z (1999) Should the North make unilateral technology transfers to the South? North–South cooperation and conflicts in responses to global climate change. Resour Energy Econ 21:67–87