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Transboundary environmental problems and endogenous technological change

A survey with particular emphasize on the climate problem

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Abstract: There are an increasing number of researches devoted to the mutual influence of environmental policy and technological development. Transboundary nature of the global warming, acid rain and other environmental problems gives rise to a particular spring in this broad flow of the research that focuses on the relationship between *international environmental regulation* and endogenous technological change. The main purpose of the paper is to make an overview of theoretical and simulation results of the analysis of this relation. The basis for efficient design of the international environmental treaty is a comparison of the outcomes of non-cooperative Nash equilibrium and the first-best social equilibrium in the presence of endogenous technological change. In the survey special attention is devoted to strategic behaviour of countries, when they deviate from the optimal environmental policy in order to affect the R&D activity of the firms engaged in imperfect competition. Then I consider the issues that focus on an *asymmetry between countries* and special conditions that should supplement the international agreement between asymmetric countries. An important feature of international cooperation is the absence of a central international regulator. Hence, an agreement should be voluntary and have an intrinsic means of maintaining cooperation. One of the ways to stabilize an environmental coalition is to link it to a more stable technological cooperation. I provide an overview of the research on the *linkage issue*.

Keywords: International environmental cooperation, Endogenous technological changes, International technological diffusion

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Content

1.Introduction

Technological change plays an important role in dealing with the climate change problem. There are several ways an emission reduction can occur: through a reduction of the emission-output ratio by means of the development of new alternative energy sources; cleaner production technology; end-of-pipe installations; or through a reduction of abatement costs by means of the development of abatement technology etc. A wide range of empirical research describes the presence of technological change and its environmental impact. For example, Grubler et al. (1999 a,b) find evidence of learning rates (i.e. changes in the cost reduction effect of investments) and S-shaped diffusion paths of technological development. It was shown in the paper that incorporating the learning effect in a global change model leads to a less environmentally detrimental impact in the future. The same result was derived in Rasmussen (2001). Simulation analysis in Dowlabadi (1998) shows that the effect of endogenous technological change on the environment depends on the sectors in which the technological change is assumed to occur. The economies of learning exhibited in oil and gas exploration and in energy-intensive sectors increase business-as-usual emission levels, while endogenous technological change in non-fossil and abatement technologies reduces abatement costs and the business-as-usual emission level.

There is a mutual influence of technological change and environmental policy instruments. Environmental policy not only alters emission paths but also affects technological development: directly via changes in the incentives for both the public and private sector to innovate and adopt environment-friendly technology and indirectly via changes in the distribution of research and development (R&D) activities among industries, changes in prices and industrial structure[1]. In this sense, technological change is *induced* by the policy instruments (ITC).

[1] A good analysis of price-induced technological change for the energy sector can be found in Dowlatabadi (1998). A carbon emission abatement policy induces R&D-activity by both energy suppliers and demanders. Tightening of environmental regulation increases total costs and hence the price of energy, thereby inducing energy suppliers to find an alternative to a fossil fuel technology and energy consumers to develop more energy–efficient technology. By means of the Integrated Climate Assessment Model (ICAM), extended by the presence of learning-by-doing (LBD) and learning-by-abating, Dowlatabadi (1998) analyses how expectations of price hikes affect technological innovation, diffusion of energy-saving technology, and the effectiveness of different policies' interventions.

In its turn, technological change and the way it is modeled affect instruments and timing of an abatement policy. There are two prevailing ways of modeling technological development: research and development (R&D)-spending and learning by doing (LBD). The difference between them is that R&D is a resource-consuming investment, while LBD is a by-product of abatement or production activities. Goulder and Mathai (2000) consider both R&D and LBD representation of ITC and show that in the presence of R&D abatement should be delayed since technological changes makes future abatement cheaper. The presence of LBD favors earlier abatement since it contributes to knowledge accumulation that reduces abatement costs. Goulder and Mahai (2000) demonstrate that ITC may have a large impact on the optimal emission tax by decreasing the tax rate in a cost-effective scenario. Goulder and Schneider (1999) find that in the presence of ITC, the economy reacts more elastically to the tax and undergoes a greater abatement. Tax imposes higher gross costs (i.e. without environmental benefits) caused by the increased abatement, but at the same time, in the presence of ITC it leads to higher net benefits. There are two reasons for this statement: higher environmental benefits and lower marginal abatement costs. Thus ITC makes the climate policy more attractive.

The majority of the research focuses on technological progress and environmental policy within country borders, on the firm or industrial level. There are good surveys on this issue in Jaffe et al.(1998, 2002) and Løschel (2002)[2]. However, the transboundary nature of the global warming and negative environmental externalities make environmental policies without international cooperation inefficient. Since an effective solution of transboundary pollution prescribes use of an international agreement, it is important to consider the mutual influence of technological development and an *international environmental* policy. To my knowledge, there is no survey of the literature that focuses on the issue of *international environmental cooperation and endogenous technological change*. This overview hopes to fill that gap.

An international environmental agreement will influence technological development. The international treaty may give direct prescriptions to participating

[2] In Løschel (2002) an international aspect was mentioned in connection with technological diffusion and spillovers.

countries with respect to domestic policy instruments, including R&D investments[3]. An indirect influence of the international environmental cooperation on the technological path occurs through the change of a domestic environmental policy caused by cooperation. The change in domestic policy affects public R&D-spending and the R&D-activity of the private sector[4]. A design of the international agreement has an impact on the technological development and the efficiency of the environmental policy measures. Buonanno et al. (2000 a,b,c) analyze an efficient design of the Kyoto Protocol in the presence of ITC driven by public R&D. They show that countries' environmental R&D-spending and abatement costs are affected by the form of the international cooperation[5]. At the same time, there exists a reciprocal effect - the way of modeling technological change influences the design of the optimal international agreement. In addition an international agreement affects technological spillovers and diffusion among the countries.[6] Rosendahl (2002) shows that the presence of technological diffusion from developed to developing countries justifies constraints in the international emission trade. Dowlabadi (1998) demonstrates that the diffusion compensates for delay in abatement. Thus, when designing an optimal international policy, participants should take into account countries' LBD-abilities, R&D-spending and technological diffusion paths.

The rest of this article is structured as follows. The second section focuses on the difference between cooperative and non-cooperative solutions of the global environmental problem in the presence of endogenous technological change. Special attention is devoted to a simulation analysis of the Kyoto Protocol. It reveals how the outcome of international cooperation changes under different ITC modeling. The analysis helps to construct an optimal mechanism of quota trading.

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[3] Another type of international cooperation implies countries' commitments to certain environmental targets with a free choice of their domestic instruments (e.g., the Kyoto Protocol).

[4] A brief overview of the country- and firm-level literature that considers environmental policy in the presence of ITC can be found in the appendix. The issue is quite important since most R&D is done within the private sector. This should be taken into account when countries negotiate an international environmental agreement or design domestic policy instruments to comply with environmental targets imposed by an international agreement.

[5] In particular, Buonanno et al. (2000 a,b,c) consider different constraints on a free quota trading.

[6] There are theoretical overviews on the diffusion issue made by Blackman (1999), Jaffe et al. (1998, 1999 and 2002).

The third section is devoted to *strategic behavior*, i.e. when countries set their environmental policy to affect the R&D activity of the firms engaged in imperfect competition. Such non-cooperative strategic behavior is likely to cause a deviation from the optimal environmental policy. The forth section considers an *asymmetry between countries* and special conditions that should supplement the international agreement between asymmetric countries. An important feature of international cooperation is the absence of a central international regulator. Hence, an agreement should be voluntary and have an intrinsic means of maintaining cooperation. One of the ways to stabilize an environmental coalition is to link it to a more stable technological cooperation. The *linkage issue* is the topic of fifth section. The final section contains concluding remarks and extensions for future research.

2. International environmental agreement versus non-cooperative Nash equilibrium

In this section I consider a theoretical basis for an optimal organization of an international environmental cooperation in the presence of ITC. The general approach in designing an efficient international agreement is to compare the outcome of the aggregate international welfare maximization in the case of international cooperation (the first-best outcome, which I will call "cooperative") with the situation of a non-cooperative Nash equilibrium. For the case of endogenous technological change the comparison has been made by Ploeg and Zeeuw (1994), Xepapadeas (1995) and Rosendahl (2002).

2.1. An international environmental agreement with knowledge modeled as a common pool

Earlier works (e.g., Ploeg and Zeeuw 1994, Xepapadeas 1995) considered knowledge as a common pool. As a result, all countries possessed the same level of technology in the cooperative case. ITC was modeled as R&D-spending on abatement technology. Therefore, countries had an additional control instrument– R&D investment. The first-best social outcome is a solution of the following dynamic maximisation problem:

$$\max_{c,I} \int_0^\infty e^{-rt} \sum_j \{U^j(c_j(t)) - D^j(S(t))\} dt \tag{2.1}$$

subject to

$$\dot{H}_i = \psi(\sum_j I_{ji}(t), H_i(t)), \quad i = A, P, \tag{2.2}$$

$$\dot{S} = \alpha(H_A)\sum f_j(t) - bS(t) \tag{2.3}$$

$$f_j(t) - I_{jP}(t) - I_{jA}(t) - c_j(t) = 0, \tag{2.4}$$

Where

U - standard utility function of consumption c,

D – damage function from pollution stock S,

b - rate of the natural removal of pollution,

H- level of accumulated knowledge,

$I_{jA}(t)$ - country's j investment in abatement technology,

$I_{jP}(t)$ - country's j investment in the production sector,

$f_j(t)$ - country's j production function,

ψ - increasing and concave function that describes knowledge accumulation,

α(H) – emission-output ratio, which is a decreasing and convex function of the technological level.

The object function (2.1) is a discounted sum of countries' utilities $U^j(c,S)$. The utilities are assumed to be separable in consumption and pollution damage, i.e. $U^j(c_j,S)= U^j(c_j)-D^j(S)$. The object function is maximised subject to production and technological constraints (2.2)-(2.4). Equation (2.2) describes technological development as a R&D process. Pollution accumulation is shown in equation (2.3). Equation (2.4) describes an output distribution between consumption and investment in abatement and production sectors for every period t. The solution of the (2.1)-(2.4) gives us first-best levels of consumption, investment and pollution across the countries.

By means of different variations of the above model both Ploeg and Zeeuw (1994) and Xepapadeas (1995) show that in the absence of the international cooperation the levels of production, consumption and, consequently, pollution are too high because countries do not internalize the environmental damage that spills over to other countries. There is a discrepancy between the two papers with respect to the deviation of non-cooperative R&D from the optimal path. The discrepancy can be explained by the difference in the modeling of technological development and pollution accumulation used by the two analyses. Xepapadeas (1995) indicates that there is under-investment in R&D for the non-cooperative case since countries do not acquire all the benefits from their R&D activity. He considers resource-saving technological changes. Pollution is associated not with an output but with one of the production inputs R. The input in the production function is in the terms of efficient unit, i.e. $f(H_P R, l)$, where l denotes other inputs. Technological development increases effectiveness of the resource and reduces consumption of the polluting resource. There is constant resource-emission rate. Thus equations (2.2) and (2.3) in the model changes into (2.2') and (2.3'):

$$\dot{H}_P = \psi(\sum_j I_{jP}(t), H_P(t)) \tag{2.2'}$$

$$\dot{S} = \alpha \sum R^j(t) - bS(t) \tag{2.3'}$$

Xepapadeas (1995) considers two ways of modeling the non-cooperative behavior. They differ in the information sets on which countries base their actions. In an open loop case the information set consists of the initial parameters - abatement and pollution accumulation. In a feedback model countries base their decisions on the current situation (i.e. current abatement and pollution) and take into account the response of other countries. Because of R&D spillovers and international technological diffusion, global R&D-investment in the non-cooperative case is lower than in the optimal case for both models. The discrepancy between the non-cooperative and cooperative cases is greater for the feedback model. In the model every country expects that others reduce their emission levels as a response to the increased total pollution accumulation and increase their R&D activity when the total technology level decreases. The expectation about the other countries offsetting behavior encourages separate country to reduce its R&D and increase emissions. Since the expectations are the same for all countries, total technological level is lower and total emissions level are higher in the feedback model than in the open-loop Nash equilibrium.

Ploeg and Zeeuw (1994) consider model (2.1)-(2.4), where technological development has a direct effect on emission-output ratio. Since they assume that increased production provides resources for R&D, the elasticity of the emission-output ratio with respect to the stock of knowledge plays a central role in the determining of

R&D-spending (in Xepapadeas (1995) the resource-emission rate is constant). In the case of the inelastic emission-output ratio, environmental damage associated with increased production exceeds the benefit from the extended investment in environmental R&D. Higher non-cooperative production makes it possible to reach a higher R&D level, than in the cooperative case,[7] but at the expense of too high pollution level. It is socially optimal to reduce total production, via reducing inputs, to manage the environmental problem even though it causes a reduction in environmental R&D. In this sense, R&D is overproduced in the non-cooperative case. In the case of more elastic emission-output ratio with respect to accumulated knowledge, the increase in production has an environment-friendly character: the benefits from the extended R&D exceed by-product environmental damage. As a result, the under-production of R&D is a likely case in the non-cooperative equilibrium since countries do not take into account the other countries' benefits from the increased common technological level. Hence Ploeg and Zeeuw (1994) do not give a definite answer about bias of the non-cooperative R&D-spending from the first-best case.

2.2. An international environmental agreement with differences in knowledge endowment

Difference in technological levels may explain the difference in emission taxes imposed on countries. For example, in Xepapadeas (1995) the efficiencies of countries' contributions to a common knowledge pool in the global optimum case are equalized after taking into account their endowment level. Regardless of the common technological level countries' contributions are not equal since countries differ in their resource endowments and the same amounts of R&D-spending have different alternative value, as they reduce the possible consumption level differently. Hence, in the global social optimum poor countries with low consumption levels contribute less to the total technical changes. This causes the differences in taxes and subsidies across the countries in a cost-effective scenario.

There are two kinds of the optimal international policies considered in Xepapadeas (1995). The first one obliges countries to contribute to R&D in the amount

[7] Ploeg and Zeeuw (1994) show it for the case of iso-elastic emission-output function $\alpha(H) = \alpha_0 H^{-w}$ when w=0,5.

that corresponds to the global optimum. Countries' commitments to join the agreement eliminate a free-riding problem. The stability of the environmental cooperation is explained by the higher technological level and a lower pollution for countries-participants and by the absence of positive technological spillovers to non-participating countries that were implicitly assumed in the paper. The second way is to tax CO_2 emissions and subsidize environmental R&D. Taxes and subsidies are designed to erase the difference between the country's valuation of emissions and R&D-investments on the one hand and optimum valuation on the other.

Xepapadeas (1995) demonstrates that in the case when a separate country gets an additional gain if its technological level is higher than average, rich countries, which are able to achieve high technological level individually, have no incentives to participate in the agreement even though their failure to join the agreement results in a higher pollution level. The countries' interests in maintaining the technological difference become an additional obstacle to achieving optimal emission and technological paths via cooperative policy. In the above work the difference in R&D-spending arises from the different production possibilities of the countries caused by different resource endowments. It leads to different policy instruments across the countries.

In the environmental literature that doesn't consider ITC an equality of marginal abatement costs across sources is a feature of the cost effective solution. In these circumstances a uniform emission tax or tradable emission quotas are adequate policy instruments. However, the difference in countries' technological potentials distorts this feature. For example, Rosendahl (2002) models endogenous technological change as learning-by-abatement dynamic process. Learning-by-abating implies that an abatement activity reduces abatement costs. In this setting the difference in policy instruments is determined by the difference in LBD-abilities across the countries. The main conclusion is that as long as different countries (firms, industry - sources, in general) have different LBD-abilities, marginal abatement costs differ in the cost-effective optimum. The cost-effective solution is not the one that equalizes marginal abatement costs but the one that equalizes marginal abatement costs after the future cost reductions of current abatement (caused by LBD-effect) is taking into account.

To demonstrate the above statement Rosendahl (2002) designs knowledge accumulation as the following learning-by-abatement process:

$$\dot{H}_t^j = \psi^j(A_t^j, H_t^j), \tag{2.5}$$

where A_t^j - is an abatement activity of country j in period t, j=1, 2 in the two-country case. The learning effect entails a positive partial derivative of the knowledge accumulation function $\psi^j{}_A$ with respect to abatement activity[8]. The accumulated stock of knowledge reduces abatement costs $C^j(A_t^j, H_t^j)$, i.e. $C_H^j(A_t^j, H_t^j)<0$.

A social planner chooses abatement levels to minimize the present value of the abatement costs $\int_0^\infty e^{-rt}\{\sum_j C^j(A_t^j, H_t^j)\}dt$ to comply with a given environmental constraint, $S < \bar{S}$. The necessary conditions of the problem give the following equation:

$$C_A^1(A_t^1, H_t^1) - \mu^1\psi_A^1(A_t^1, H_t^1) = C_A^2(A_t^2, H_t^2) - \mu^2\psi_A^2(A_t^2, H_t^2) \tag{2.6}$$ ()

where μ^j - is the shadow price of the knowledge stock for the region j. The equation shows that marginal abatement costs are equalized across the regions only after the LBD effect is taken into account.

However, it does not necessarily mean that environmental taxes differ among the sources. If the benefits from the induced technical changes are fully appropriated by the country (source), optimal abatement is achieved since in this case the private value of the abatement coincides with the social optimum. Rosendahl (2002) demonstrates it as follows. There are N identical small firms in each region. An individual firm minimizes

$$\int_0^\infty e^{-rt}\{c(a^s, h^s) + \tau^j(e^0 - a^s)\}dt,$$

where small letters are used to indicate a firm-level case,

e^0 - business-as-usual emission level,

τ^j - emission tax,

In equilibrium $a^s = A^j / N$.

[8] A comparison of (2.2) and (2.5) reveals the difference in R&D and LBD processes. In the case of R&D, investment (*I*) is a driving force of technological development (see 2.2), while in the case of LBD knowledge is a result of abatement activity (A), see 2.5.

Assume the learning effect to be a weighted sum of abatement within the firm (internal ITC) and total abatement in the region (external ITC), i.e. the firm has the following learning function

$$\dot{h}^s = \psi^j(\varphi a^s + (1-\varphi)A^j, h^j),$$

where φ is a parameter between zero and one. If φ is equal to one the ITC is a totally internal effect. If φ is zero, the ITC occurs only due to the spillover effects within the region. Equation (2.7) is one of the necessary conditions for the firm's cost-minimization problem:

$$C_A^j(A_t^j, H_t^j) - \varphi^j \mu^j \psi_A^j(A_t^j, H_t^j) - \tau_t^j = 0 \quad (2.7)$$

A comparison of (2.5) and (2.7) lets us derive a condition (2.8) for the optimal tax policy.

$$\tau^1 - (1-\varphi^1)\mu^1\psi_A^1(A_t^1, H_t^1) = \tau^2 - (1-\varphi^2)\mu^2\psi_A^2(A_t^2, H_t^2) \quad (2.8)$$

From (2.8) one can see that if the ITC is totally internal, i.e. φ^j =1, the optimal tax rate is equal across the two regions.

2.3. Analysis of the Kyoto Protocol and flexibility mechanisms

Discussion around a cost-effective design of the international agreement based on the allocation of emission quotas (the Kyoto Protocol) has spurred theoretical and simulation analysis of the agreement. I limit this overview to the studies that take into consideration ITC.

There are three flexibility mechanisms which are the subject of the analysis: emission trading, Joint implementation (JI) and the Clean Development Mechanism (CDM). Let us start with ceilings on quota trading. The main argument (see Hourcade et al. 1999) in favor of constraints on the emission trading is that the ceilings limit the possibility to buy quotas to comply with the Protocol, and thus induce countries to do most of the abatement via domestic measures. It increases incentives to carry out environmental R&D. As a result it reduces the long-run cost of the abatement option. Moreover, environmental R&D may spillover to other sectors and thus speed up the "engine of growth". It alleviates the detrimental impact of the climate change control on long-run per capita income and welfare. The opposite view (e.g., Convey, 1999) is that the restriction of carbon trade increases the mitigation costs of the cooperating countries and reduces the incentives of the countries to enter the agreement. Besides, the resulting decreased demand for carbon quotas reduces the R&D incentives of countries that sell the quotas.

Simulation analysis of the Kyoto Protocol also does not give a unique answer with respect to constraints in a free trade scenario for quota market. Rosendahl (2002) demonstrates that a uniform tax or free quota trade is a cost-effective only if the benefits from induced technical change are fully appropriated by the source (country, firm). However there is empirical evidence of technological spillovers among the sources. For example, Gustavsson et al. (1999) show that there are domestic within-industry, economy-wide spillovers and global spillovers among open economies. The presence of the spillovers implies different optimal taxes or constraints on the emission quota trade among the pollution sources.

Due to Rosendahl (2002), a free quota trade does not lead to cost-effectiveness because of the difference in countries' LBD-abilities. Simulation analysis shows that the global cost savings from an implementation of the cost-effective scenario instead of a free quota trade are small unless there are substantial learning effects. At the same time, the distribution of abatement costs between the regions is altered significantly. It may cause significant (re-) negotiation costs.

However, if the diffusion[9] from industrialized countries to developing countries is a significant determinant of technological growth in the developing countries, the difference between the optimal policy instruments (leading to a cost-effective outcome) for the two groups of countries increases. Rosendahl (2002) demonstrates that in the presence of technological diffusion industrialized countries with higher LBD abilities should meet higher marginal abatement costs than developing ones. It makes the industrialized countries carry out considerably more abatement in the cost-effective outcome. Hence in the presence of economy-wide technological spillovers and diffusion

[9] To model the diffusion process Rosendahl (2002) supplement the knowledge accumulation process (2.5) with a new diffusion component $\theta^j(H_t^j, H_t^{-j})$, which is non-decreasing in other countries' technology H_t^{-j}. The new equation describing knowledge accumulation has the following form $\dot{H}_t^j = \psi^j(A_t^j, H_t^j) + \theta^j(H_t^j, H_t^{-j})$

between developing and industrialized countries a cost-effective international agreement implies higher taxes for developed countries and constraints on the free trade between industrialized and developing countries on quota market. Rosendahl concludes that ”including the developing countries in the international environmental agreement may be far less important than it is discussed”.

In contrast to Rosendahl, a simulation analysis[10] of the Kyoto Protocol by Buonanno et al. (2000 a,b,c) demonstrates that participating countries gain a lot from free trade of quotas and other flexibility mechanisms. Endogenous technological change was modeled as R&D-investments that contribute to the knowledge accumulation, which reduces the emission-output ratios (called “environmental technical changes”). Total compliance costs are lower in the presence of endogenous environmental technical change. It is explained by two effects: i) reduction of the emission ratio caused by R&D-investment and ii) a lower price for permits because of decreased demand and increased supply on the quota market. There is a negative correlation between R&D-spending and the net import of permits for buyer countries (USA, EU, Japan). It means that R&D and emission trading are substitutes for these regions. In Buonanno et al.(2000 b,c) special attention was devoted to ceilings on trade in order to check the preposition that full access to a permit market provides no incentives to undertake domestic action. The simulation analysis shows that an introduction of the ceilings increases the R&D effort of the buyer countries (USA, Japan, EU) and foster technological innovations. These countries spend the highest amount on environmental R&D in the case where trading is not allowed, i.e. when all the abatement is carried out through the domestic measures. However what is important for us is not the design of the agreement that induces highest environmental R&D but the design that provides the lowest compliance costs. The simulation analysis shows that ceilings increase mitigation costs. The negative effect from the increased mitigation costs on long-run economic growth is stronger than the positive effect from increased R&D-activity. It was demonstrated that the free-trade

[10] The ETC-RICE simulation model was used. The world is divided into six macro regions: USA, Japan, Europe, China, the Former Soviet Union (FSU), Rest Of the World (ROW). Within each region a central planner chooses the optimal paths of investment, R&D expenditures, emission abatement and the amount of permits that will be bought or sold by the country that maximizes the present value of per capita consumption.

regime gives the lowest ratios of the compliance costs to gross national products[11] in the OECD. In other countries the R&D efforts depend on their role on the permit market. The Former Soviet Union (FSU) carries the largest R&D when there is trade among the Annex-1 countries since, according to simulations, the FSU is the only seller in this case. The FSU uses R&D spending as a strategic variable. By increasing its R&D the country gives a sign of its expansion on the permit market. When trade is allowed for all countries the FSU is no longer the single seller. Thus the FSU cannot use R&D-spending strategically. With the expansion of trade China and the Rest of the World (ROW) got an opportunity to participate in the emission trading. They increase their R&D-investments to gain permits available for sale. With the expansion of trade the total R&D effort of this group of countries decreases since the extension of R&D activity in the ROW and China is less than the reduction of R&D in the FSU. This is explained by the strong strategic effect that disappears with the expansion of trade. For that group of countries ceilings on trade reduce the demand for their permits and have an adverse effect on their welfare and R&D-efforts.

Hence, the simulation in Buonanno et al. (2000) does not support the hypothesis that ceilings have a positive long-run impact on the economical growth via stimulating R&D. Both abatement and mitigation costs decrease when more countries are allowed to trade even in the presence of ITC.

Some countries benefit from international knowledge spillovers, while others lose. The simulation demonstrates that an introduction of international knowledge spillovers reduces total welfare compared to the case without spillovers. A free-riding possibility induces countries to reduce their R&D. It increases emission-output ratios and hence total emissions. Together with the unchanged abatement targets it makes the reduction of the emission level either through domestic arrangements or through a purchase of permits more costly. At the same time, the decreased R&D activity of the seller countries reduces the supply of permits. It increases the price for permits and the costs of the purchase. As a result, the spillover effect tends to raise overall mitigation costs. It is worthwhile to note that spillovers matter only in the presence of induced

[11] That takes into account a positive effect of environmental R&D.

environmental technological changes, since it is only in this case that R&D-effort has an impact on emissions.

Buonanno et al.(2000a,b,c) obtain the opposite conclusion to the one of Rosendahl (2002). The reason is the assumption made in Rosendahl (2002) that only Annex B countries experience LBD while in the non-Annex B countries technological change is either autonomous or caused by the technological diffusion from the industrialized world. It leads to the optimal scenario in which most abatement should be done in Annex B countries. It justifies the constraints in quota trading among Annex B and non-Annex B countries accompanied with free trade among the Annex B group.

It is worthwhile to note that while Rosendahl (2002) derives a cost-efficient scenario and optimal distribution of quotas, Buonanno et al. (2000) do not consider such a benchmark case, but the least costly mitigation of the targets of the Kyoto Protocol among those scenarios they do simulations for. The Protocol sets emission quotas without taking into account an endogenous character of technological changes. The absence of a benchmark case does not allow us to judge the optimality or distortion of the path of the technological progress caused by various designs of the international agreement.

In addition to quota trade there are two other flexibility mechanisms (Joint Implementation and the Clean Development Mechanism). The CDM incorporates the option to transfer investments within specific emission reduction projects from developed to developing countries. Similar projects between developed countries are called JI. Since these flexibility mechanisms are aimed at equalizing marginal abatement costs among the countries, the arguments about the necessity to equalize marginal abatement costs above may also be applied to JI and the CDM. However, the two flexibility instruments have additional advantages since they can be viewed as a means of technological transfer among the countries. Thus the full analysis of the flexibility mechanisms should take technology transfers into consideration (see Millock, 2000). Simulations made by Kemfert (2001) support the elimination of constraints on emission trade and an implementation of the CDM and JI, as these mechanisms not only reduce the abatement costs of donor countries, but induce a self-enforcing investment process, expansion of carbon-free technology and additional economical growth in the host countries. The argument is especially important for the CDM, since technological diffusion caused by the mechanism is a driving force of the technological development in a developing country. I leave the detailed discussion of the role of the CDM in the diffusion process for the next section.

3. International treaties and diffusion of environmentally friendly technology

3.1 An international technological diffusion as a source of technological changes in developing countries

Budget constraints and low concern about environmental issues limit technological change and implementation of environment-friendly technology in developing countries. Hence these countries have inferior and often more polluting technologies. Empirical analysis shows that the majority of knowledge is generated in the industrialized world (see Worell et al. 2001). The low stock of knowledge in developing countries results in underemployment of their LBD abilities. This large asymmetry among countries causes unequal conditions in an international environmental agreement for industrialized and developing countries.

Low weight put on the environmental problem by the governments in developing countries, institutional and economic barriers make public spending on environmental R&D problematic. In these circumstances the private sector's investments become an engine of technological change. A great part of R&D is done within the private sector. Thus special attention should be devoted to creation of incentives for the private sector to invest in environmental R&D (see appendix). However, there has been little success in the creation of incentives in developing countries. There are a number of reasons for this. Apart from the lack of regulatory pressure and weak environmental regulation and pollution control in developing countries, the following barriers exist (see Blackman 1999, Parry 2001, Worrell et al. 2001):

- Decision-making procedure. For developing countries it is typical to have a rigid hierarchical structure. Such structure and a paucity of organizations occupying the few niches in a given area lead to a strong and closed network of decision makers who often benefit from the preservation of the status quo. Their priorities are unlikely to include cost-effectiveness and energy saving.

- Lack of information. For many developing countries there is a lack in the capacity of information dissemination. This is true for both consumption and production.

- A shortage of trained technical personnel and human capital. Scientists and engineers are more scarce in developing countries
- Difficulties in the enforcement of patent rights to protect firms that were successful in their R&D-efforts. Strong patent rights stimulate innovation but make adoption (diffusion) more costly.
- High inflation rates, lack of infrastructure increase risks for foreign and domestic investors and limit investments in long-term innovation projects.
- A shortage of financial sources because of undeveloped capital markets.

These barriers make the import of environmentally sound techniques from industrialized countries to developing ones an important determinant of the technological progress in developing countries.

The diffusion process however is also quite troublesome in developing countries. The barriers for innovation activity listed above explain also a slow diffusion process. In addition to them, there are some specific barriers for the international diffusion process (Worrell et al. 2001[12] and Blackman 1999). As a rule, technology is developed for a particular region or scale. The fact that technology lowers production costs in the industrialized countries may not necessary mean that it can be successfully adopted in developing countries. There is a wide range of factors apart from profitability that influence diffusion. They include firm-, sector-, and country-level characteristics: firms' size, factor prices, human capital, infrastructure, the profitability of old capital, LBD, scarcity of inputs vital for a new technology, search and transaction costs for new technology, and institutional factors. There is likely to be a systematic difference between developing and industrialized countries. For example, labour is more costly in industrialized countries. Hence, labor saving technologies are more profitable in industrialized countries. Differences in technology is an additional reason why local investors experience difficulties in the assessment and adoption of foreign technology. Besides, national protection policies (e.g., trade and investment policy) may reduce the inflow of foreign capital and technology.

Besides the barriers listed above there are special obstacles for innovation and diffusion processes of energy efficient technology (see Worrell et al. 2001). First, there is

[12] In Worrell et al.(2001) interaction between firms is considered to be a main engine of the diffusion of energy efficient technology.

a high fluctuation in energy prices and hence in the profitability of investment in developing countries. Empirical studies indicate that energy prices have a critical impact on the adoption and innovation of energy-saving technologies (e.g., Blackman 1999). In many developing economies energy is highly subsidized. A tax on energy increases prices and spurs innovation and adoption of environment-friendly technology. The second barrier is non-inclusion of external costs of energy production and use in the energy price, that undermines firms' motivation to abate. Third, it is difficult to demonstrate and quantify the impact of energy efficiency measures on the firm level.

3.2. Should the developed countries foster technological diffusion to developing countries?

There is a clear need for public measures to deal with the highlighted problems. Worrell et al. (2001) conclude that countries that spend a lot on adoption of new technology to local conditions are more successful in technology diffusion within the country.

The shortage of domestic resources and policy instruments in developing countries leave space for an international agreement to foster technological development. It may be especially helpful in the following stages: provision of access to environmentally sound technology developed in the industrialized world, assessment and adoption of new environment-friendly technology and building-up an informational infrastructure. An important arena for cooperation between industrialized and developing countries involves the development and strengthening of local technical and policy-making capacities, contributions to the development of human capital, education and technical training. There is a great opportunity to transfer knowledge via promotion of the activity of large international companies and international cooperation between firms. An international agreement can provide the basis for the long-run support of projects that include technological transfers (Worrell et al. 2001). It entails the creation of a special international policy framework that helps to create environmental, energy-saving and trade incentives as well as taxation and patent legislation. The framework is aimed to provide the right signals to all parties involved in the technological changes as well as to help to develop innovative concepts for technology assessment, financing, adaptation and development of the environmentally sound technology.

Analysis made in Yang (1999) brings empirical evidence in support of technology transfers. By a simulation model[13] Yang (1999) shows that industrialized countries (the North) gain from unilateral financial transfers to the developing countries (the South), which are interpreted in the model as real technology transfers, aimed to reduce emissions in the South even if the North maximizes its own rather than a total welfare function. The reason is that the North is suffering from the environmental negative externalities of the South while the South has no means to reduce its emissions.

Is it more preferable to induce the South to abate or to transfer technology from the North? The simulations show that the global emission level is higher and total welfare is lower when the South does some abatement without technological transfers compared to the case when only the North abates and transfers environmentally-sound technology to the South. Hence, the results of the simulation justify technological environmental transfers from the industrialized world to developing countries. This conclusion may be strengthened by the following factors omitted in the model of Yang (1999): i) the presence of technological spillovers from the North (in the model technological transfers are assumed to be costly for the North), ii) learning-by-abatement or iii) an additional advantage from transfers of the environmental sound technology when it spurs R&D and technology development in other sectors of the South.

The process of technological diffusion has received special attention in the theoretical literature. With a general equilibrium model for two countries - donor and recipient - Chao et al (1999) derives conclusions similar to the ones obtained in Yang (1999). He shows that aid tied to environmental clean-up may lead to a win-win situation for both countries despite of the terms of trade deterioration. The situation may change if a benefit from the improved environment is small.

Technological transfers as a means to provide sustainable development were considered in Xepapadeas (1997). In the model, a social planner derives an optimal output path that takes into account damage caused by the by-product pollution. Both production and abatement sectors have increasing returns to scale as a result of knowledge accumulation. Under some special assumptions about the production and emission-output functions the optimal control problem of the social planner has two

[13] The model is a modified version of the RICE model

stable solutions[14]: with and without the possibility to accumulate environmental capital. Which of them the economy ends up in is determined by the initial level of abatement and production knowledge. The lack of knowledge, which is likely to be the case for the economy at a low point on the development ladder, does not allow the economy to exploit the increasing returns in abatement technology. A vicious circle arises: abatement stock is low, the economy reduces output to keep pollution at a socially optimum level, moderate output is not enough to increase the stock of knowledge etc. Thus the poor economy is trapped in a low growth path because of the environmental restrictions. Technological transfers in the form of contributions to abatement capital accumulation may reduce the emission coefficient, and thus relax the environmental constraint. This makes it possible for the economy to reach the path of unbounded growth. The recommended policy is one of subsidizing research in the abatement sector. Strict international environmental regulation may trap the developing country in the low-growth region. Hence the international agreement should be supplemented by the

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[14] The two stable equilibria (where $\dot{h}_A = \dot{h}_P = 0$) are derived when the social planner solves the following optimal control problem (3.1)-(3.4).

$$\max \int_0^\infty e^{-rt}\{U(c(t)) - D(S)\}dt \qquad (3.1)$$

subject to

$$\dot{h}_i = h_i \psi_i \left(\frac{I_i}{h_i}\right), i = P, A, \qquad (3.2)$$

$$\dot{S} = \sum \alpha(h_A, H_A, H_P) f(h_P, H_P) - bS, \qquad (3.3)$$

$$f(h_P, H_P) - I_P - I_A - c = 0, \qquad (3.4)$$

Where

h_P - state of knowledge used by the firm in production as an input, $H_P = nh_p$ - aggregate level of production knowledge, n is the number of firms in the economy,

h_A - state of abatement technology, $H_A = nh_A$ - aggregate level of abatement knowledge,

$f(h_P, nh_P)$ – production function, which is increasing and convex for in h_P .Hence there is an increasing marginal productivity of knowledge,

$\alpha(h_A, H_A, H_P)$ - output-emission ratio, which is decreasing in both h_A, H_A and non-increasing in H_P. The last assumption means that developed countries have lower emission-output ratio. There is a level of abatement capital $\tilde{h}_A$ such that for the stock of abatement capital, lower than $\tilde{h}_A$, there is no pollution reduction. For the level of environmental capital above $\tilde{h}_A$ the reduction in the unit emission ratio is increasing in absolute value.

international transfers of abatement knowledge, which help the country to overcome the threshold point to move to a "good" equilibrium.

Dowlatabadi (1998) introduces endogenous technological changes in the form of LBD in abatement and production sectors in the Integrated Climate Assessment Model (ICAM) and analyses the role of a carbon-saving technological diffusion to a non-Annex region. He shows that the accelerated technological diffusion from the most industrialized region to other regions leads to a decrease in total energy use, CO_2 emissions[15] and mitigation costs. In addition, it was demonstrated that these technology transfers act as a substitute for the earlier control, i.e. diffusion reduces the welfare loss from delay of the environmental policy. Dowlatabadi (1998) concludes that it is optimal to subsidize technological transfers and gives a mechanism to derive the optimal subsidy.

3.3. The CDM as a means of technological diffusion

In the discussion of technological diffusion between developed and developing countries it is important to consider the effectiveness of the CDM that plays an important role in the technological development of the developing countries. Kemfert's (2001) simulation analysis of the World Integrated Assessment General Equilibrium Model (WIAGEM) illustrates that the CDM, like other flexibility instruments, not only decreases the mitigation costs of the developed countries but also stimulate self-enforcing investment activities in host countries and contribute to sustainable development of the host country. They augment the energy efficiency by application of new carbon-free technologies. It increases the share of new less carbon intensive technologies. An additional advantage of the CDM is that it is a means to involve developing countries in the environmental agreement.

It is worthwhile to note that the CDM is not free of flaws: besides the specificity of the technology to particular country's conditions mentioned above, it is a donor country that chooses a technology. Donor's interests may lead to a sub-optimal technology choice (see Schumacher and Sathaye, 1998). Another problem is "cream-skimming", when the Annex-1 countries exploit the cheapest abatement options. If, at a later time, the host country will be subject to a binding emission reduction target, it is left

[15] Thus the diffusion of cleaner technology outweighs the carbon leakage effect.

with more expensive abatement options (see Rose et al. 1999). A host country, hence, is interested in the postponement of the CDM project. One of the possible policy instruments to compensate for the exploitation of the cheapest options is to design transfer payments (considered in Millock, 2000).

One of the major difficulties in the implementation of the CDM is an assessment of its net effectiveness in a host country since the baseline emission scenario is not observable. The problem is augmented by asymmetric information between investor and host countries and a difficulty in monitoring actual emission reduction and costs. An investor country is interested in overstatement of its contribution, while the expectation of stricter constraints, which may be imposed on the host countries in the future, reduces the incentives of host countries to enter the CDM projects[16].

Millock (2000) shows that some particular intrinsic features of the CDM help to overcome the problem of asymmetric information and to create a self-sustained agreement. One of them is a positive correlation between commercial rent of the project shared by the participants and emission reduction potential. The knowledge of the commercial rent attached to the project allows an investor to estimate real emission reduction more accurately. An alternative way is transferring the abatement technology to the host country. This provides correct incentives for the truthful reporting of emission reductions in the presence of asymmetric information. A host country is then free to exploit the technology for other revenue-producing options, including further emission reduction to generate additional credits for sale on international emission markets. Without the transfers, a host country is interested in exaggeration of its costs to get higher compensation for "cream-skimming". Primary requirements for the successful transformation of technology include free information flows, a well working supporting infrastructure, and training of local management.

The next concern related to the CDM is the carbon leakage effect. Since investment in energy intensive production of the host country reduces its unit production costs, which may cause higher energy use. It increases the emissions in outsider countries. To avoid the carbon leakage effect, the CDM projects should be focused on the

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[16] Note that a host country is a developing one and at the present time it has no binding emission constraints.

replacement of existing capacity by cleaner production technologies (Bollen et al. 1998). Thus the ITC, i.e. the development of the cleaner technologies in industrialized countries and their consequent diffusion to developing countries, counteract the carbon-leakage effect.

In the bottom line of the section it is worthwhile to summarize that theoretical and simulation analysis reveal the importance of international technological diffusion since it spurs technological progress in developing countries and increases total welfare. An international environmental agreement has to take into account the diffusion process and promotes it via supplementary mechanisms, e.g., the CDM.

4. Strategic R&D and international environmental agreement

An environmental policy influences the costs and hence the profits of firms that participate in international trade. By deviating from the first-best Pigovian environmental policy, governments try to protect domestic firms. However, only an imperfection in the product market causes distortion in non-cooperative environmental policy, while the competitive market retains the first-best Pigovian environmental policy (see Ulph, 1996 a,b). There are two concerns with respect to strategic possibilities in the environmental setting. On the one hand, environmental policy may be set too lax in order to reduce firms' costs and help domestic firms to capture rents in international trade – so called "eco-dumping". An alternative view has its roots in Porter's (1991) case-studies. Based on the studies Porter (1991) has advanced the proposition that tight environmental regulations can actually enhance international competitiveness over the long run. Tight regulations induce domestic firms to innovate and lower costs ahead of their rivals. In this section, I consider the theoretical literature that investigates the question how the strategic setting of environmental policy in the case of imperfect product markets (duopoly, oligopoly) distorts the socially optimal environmental policy. I look only at those studies that explicitly model the effect of the environmental policy on firms' R&D activity.

A usual framework used in these studies is a three-stage game model[17]. There are two firms located in different countries. Thus the firms are subject to different

[17] E.g. Ulph (1994), Ulph (196 a,b).

environmental regulations. They compete on a third market[18]. Each firm has complete information about its competitor's technology. In stage 1 governments take as given the instrument choice of the rival government and choose their own environmental policy to maximize welfare. In stage 2 each producer takes as given domestic environmental policy and its rival's investment in R&D and chooses its level of R&D investment to maximize its profit. Finally, in the stage 3 each producer takes as given all the choices made at previous stages and output (or price, depending on type of competition) of its rival and chooses its level of output (or price) to maximize its profit.

Barrett (1994) concludes that when only governments act strategically, they set weaker environmental standards under Cournot competition in the product market and stricter ones under Bertrand competition. Ulph (1996 a,b) introduces ITC in the model and confirms Barrett's findings. He assumes that firms' choice of cost-reducing R&D (a process R&D[19]) is dictated by their strategic motivation. Ulph (1996 a,b) concludes that an inclusion of strategic behavior of the firm leads to a less distorted environmental policy. However the set of assumptions - local nature of the pollution, focus on the countries' and firms' strategic behavior, rather than on their incentives to act cooperatively – preclude us from making precise conclusions about the direction and size of the bias in environmental regulation caused by the strategic motives.

The case of transboundary damage from emissions was considered in Ulph (1994). He compares the outcomes of cooperative and non-cooperative settings of environmental policy in the presence of a Cournot duopoly on the product market. It was shown that when R&D is used as a means to reduce production costs, but not as a strategic instrument in the production market, a cooperative environmental tax exceeds marginal damage (since now the country takes into account its environmental spillovers on the other country), while a non-cooperative tax is lower than marginal damage (lax environmental standards help domestic firm to capture the gain on the product market). For the analysis in the presence of a strategic issue Ulph (1994) considers two types of

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[18] By assuming that competition occurs on the third market the model excludes a consumption surplus from the welfare function.

[19] I.e. accumulated knowledge reduces production costs $C^P = C(Y, H)$ and $\frac{\partial C^P}{\partial H} < 0$, where Y is production level and H is the stock of knowledge

R&D interaction. The first one is called a non-tournament model. In this model firms may innovate simultaneously although there is no possibility to imitate the innovation. The second one is called a tournament model. In the model only the first firm, successful in innovation, gains the benefits from the innovation. Hence firms are engaged in an innovation race.

It was shown that it is difficult to make a precise conclusion about the direction of the bias in environmental policy. For example, in the tournament models[20] competition typically produces an excessively high level of R&D spending. It explains why governments set a lower tax when they act non-cooperatively compared to the cooperative case since they do not want to increase the R&D over-investment that burdens the domestic firm.[21] This case does not confirm the Porter hypothesis.

In the non-tournament model the comparison of non-cooperative and cooperative taxes depends on the nature of the emission function. It is not clear any more that an increased tax encourages the domestic firm to do more R&D because of the following two effects. On the one hand, the increased tax directly increases marginal incentives for the domestic firm to invest in R&D. On the other hand, the investment raises costs, which lowers the incentives to reduce costs by spending on R&D, given that profit function of the firm is decreasing and convex in its costs. At the same time, increased costs for the domestic firm gives a competitive advantage to its rival on the international market. It gives the rival an opportunity to lower costs further through investment in R&D. Although it is clear that costs for the firms change in opposite directions, the definite effect of the tax on costs depends on the form of the emission function. In the environmental setting it is thus critical to derive the response of the firms' costs to domestic taxes.

Ulph and Ulph (1996) analyze the strategic setting of environmental policies when firms are acting strategically in the non-tournament modeling of the R&D competition. They extend the model of Ulph (1994) containing environmental R&D by

[20] It is assumed that the competition threat, which is the difference between present value of profits from winning and profits from loosing, is less than the profit threat, which is the difference between current profit and profit from winning.
[21] The result was obtained for the particular model.

process innovation[22]. This extension does not change the result made in Ulph (1994). The rationale is that if the nature of the environmental R&D function is such that firms choose such amounts of environmental R&D that will exactly offset the effect of the emission tax, then the tax may have no impact on the amount of the process innovations that firms would carry out. If the nature of the environmental R&D function is such that the increase in the emission tax causes the domestic firm's costs to rise, it may be an argument to relax environmental policy. But the higher costs will also discourage the process R&D, so that it would just reinforce the argument for relaxing the environmental taxes. Finally, if the nature of the environmental R&D is such that the increase in the emission tax causes the domestic firm's costs to fall, it makes it is reasonable to tighten environmental policy. At the same time, the fall in costs will induce the domestic firm to do more process R&D, which reduces costs further. Thus the innovation process reinforces the incentives to increase emission taxes and mainly strengthens the effect of the environmental R&D. The same results were derived for environmental standards.

Carraro and Topa (1994) consider the influence of an internationally coordinated tax policy on the innovation of environmental friendly technology. Without environmental regulation, firms use an old technology that has a constant emission-output ratio. The environmental tax imposes additional costs on the firms and induces them to abate. With the old technology the only way to abate is to reduce output. Sufficiently high additional costs make it more preferable for the firm to use an alternative abatement opportunity – to develop a new environmentally sound technology that enables the firm to reduce the emission-output ratios. The new technology is not available unless some R&D is carried out. To introduce the new technique within a time t_j a firm j (where j=1 or 2 for the case of two firms) has to spend a monetary amount, which is described by the deterministic, decreasing and convex function $p(t_j)$. The function includes both R&D-expenditure and adoption costs (costs of adjustment to the productive processes). The convexity of the function implies that if a firm tries to accelerate the time of innovation, it entails not only higher total costs, but also higher marginal innovation costs. It is also assumed that there are no R&D spillovers or a possibility to imitate the innovation, so

[22] Environmental R&D reduces emissions per unit of output (e.g. see equation (2.3)), while the process innovation reduces the costs of output (see footnote 19).

each firm has to invest in the new technology by itself (a "non-tournament case" in Ulph's terminology). The time of investment, and hence innovation time t_j, is determined by each firm in the beginning of the innovation game. The firms are engaged in Cournot competition. Carraro and Topa (1994) consider two cases of environmental regulation: with and without international cooperation. In the case of international cooperation an environmental tax rate is set centrally by the international agreement, while in the non-cooperative case it is determined individually by every country. It was shown that the tax rate is lower for the non-cooperative case, even though it may impose costs sufficient to induce an innovation. It implies that in the non-cooperative case the firm's profit and emissions are higher, but the total welfare[23] is lower than in a cooperative case. The source of the difference between the two cases is that in a non-cooperative case the country neglects both the harm to a producer of the other country caused by the change in the domestic environmental policy and negative environmental spillovers in the other country.

Albeit the fact that the firms are identical, there is sequential rather than simultaneous innovation[24] in both cooperative and non-cooperative cases, either when the firms' actions are driven by private motives or aimed to obtain a social optimum (in the last case firms take into account environmental damage). The explanation is the following: if both firms innovate at the same time, they lose the competitive advantage of being the first innovator, while paying the high R&D costs caused by the willingness to innovate sooner. One of the two firms thus prefers to save R&D costs and innovate later (a chicken game). In a non-cooperative regime both private and social innovation dates are later than in the cooperative one, since without international cooperation the private and social gains from innovation are smaller.

In both cooperative and non-cooperative cases the private dates of innovation R&D are delayed in comparison with the ones determined by the socially optimum considerations. Thus the optimal policies in either cooperative or non-cooperative cases consist of both environmental taxes and R&D subsidies. It results in earlier and greater abatement effort and larger total welfare. The difference in the innovation dates between

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[23] In the model the welfare function contains both the consumer surplus and the profit of the firm.
[24] I.e. firms choose different timing, t_1 and t_2, of the innovation process.

social and private cases is smaller for the non-cooperative equilibrium. This can be explained by the fact that in the non-cooperative case a government takes into account only the profits of a domestic firm. The firm that innovates second suffers a loss in competitiveness until it innovates. Each government tries to induce a domestic firm to innovate earlier when it innovates second. In a cooperative case the governments prolong the diffusion time, since they take into account that the total industry profit is higher when only one firm innovates than when both do.

Thus, the theoretical findings confirm the proposition that an imperfect product market and a possibility to use R&D strategically distort the socially optimal environmental policy. However the direction and the size of the bias are sensitive to a variety of related factors: the type of competition on the product market, the nature of technological progress and the way it affects production and environmental costs. These factors should be considered in the process of designing of the global policy measures (an international environmental agreement).

5.Stability of the environmental agreement and R&D-cooperation

The voluntary nature of the international treaty and the absence of a "supranational authority" raise the problem of the sustainability of the environmental coalition. Since a single country appropriates only a part of the damage from its emissions the incentive to free-ride on other countries' abatement effort is very strong. There are two classes of models. First, there are short-period models where countries bargain over emissions. Second, there are models that represent an agreement as an infinitely repeated game. Both classes show that the stable environmental coalition is possible only for a small number of countries (e.g., Barrett 1992, Carraro and Sinescalco 1991,1992).

At the same time, the small number of cooperating countries does not allow full appropriation of the benefits of an international environmental agreement. Hence there a need for additional policy instruments to enlarge the coalition arises. The common way to deal with the problem is welfare transfers or side payments (e.g., Carraro and Sinescalco 1995). Countries of the small sustainable environmental coalition transfer their gains obtained from the coalition to the non-cooperating countries to induce them to join the agreement.

An alternative way was proposed in Carraro and Sinescalco (1995). It is a linkage[25] of the unstable environmental coalition to a more stable cost-saving R&D cooperation, which involves an excludable[26] positive externality and increases the coalition welfare. These two features - i) the benefits from R&D cooperation and ii) an excludability of the benefits - offset the free-riding incentives of the countries participating in the environmental cooperation. It was shown in Carraro and Sinescalco (1997) that the linkage of the two coalitions expands the dimension of the environmental coalition. They consider an oligopolistic industry with firms located in the different countries and engaged in Cournot competition. Every firm is subject to domestic environmental regulation. The decision process consists of three stages. In the first stage an individual country decides whether to participate in the linked coalition and the stable coalition is formed. The decision of whether to join the coalition follows from the country's welfare maximization. Optimal abatement levels of cooperating and non-cooperating countries are determined in the second stage. In the last stage, firms determine their levels of production and R&D-expenditures. If the country joins the environmental coalition the environmental regulation imposed on the domestic firm are stricter than if it does not. If a country joins the R&D cooperation, the domestic firm gets access to the other firms' R&D and benefits from it, i.e. there are excludable positive R&D spillovers. Carraro and Sinescalco (1995, 1997) show that if the environmental coalition is profitable but unstable, whereas technological cooperation is profitable and stable, the joint coalition is more stable and profitable than the two separate negotiations.

In their comments on the paper of Carraro and Sinescalco (1995), Miller and Zhang (1995) expand the model and show that not only the linkage to a cost-saving R&D cooperation results in a more stable coalition but the positive externalities from the development of the very abatement technology helps to stabilize the environmental coalition without any linkage outside the environmental cooperation. The natural

[25] A linkage means that the signing of one agreement is conditional on the signing of another.
[26] Excludability may be achieved through the patent system.

proposition, following from the discussion, is to concentrate directly on the R&D in the environmental protection technology.

The main critique of the Carraro and Sinescalco's linkage model is the excludability of the R&D spillovers (e.g., Schmidt 2000). It is not clear why the degree of R&D cooperation is higher for the cooperating countries than for the outsider countries of the environmental coalition; and why the outsider countries are not able to create their own R&D cooperation. One possible explanation, however, may be an asymmetry of the countries (Carraro and Sinescalco assume identical countries), e.g., the environmental coalition is created within the industrialized countries that own more advanced technology and are able to organize more profitable R&D cooperation.

The second critique is why the benefits of R&D cooperation were not exploited outside of the environmental cooperation. For example, Katsoulacos (1997) notices that countries and firms participate in research joint ventures (RJV) that allow them to gain from increased innovation spillovers without cooperating on the environmental issue. Contrary to Carraro and Sinescalco (1995, 1997), Katsoulacos (1997) makes the more realistic assumption that it is not governments but firms that invest in R&D and participate in RJV and hence determine the level of the informational sharing. The term "information sharing" means here the sharing of the achievement from the R&D activity. Firms engage in the R&D cooperation even in the absence of any policy inducement and are able to choose their R&D and informational spillovers from R&D discoveries regardless of the environmental cooperation. However it was shown that when firms set their R&D and determine the rate of their information sharing, both parameters are chosen below the social optimum. When governments decide whether to enter the environmental coalition, they may link the international environmental agreement to the RJV by making R&D subsidies to the RJV. The R&D subsidies aim to correct possible market distortions. It is shown that stable environmental cooperation can be achieved through such RJV agreements with clauses for environmental policy. Countries have incentives to cooperate in subsidizing R&D and none of them has an incentive to defect from the environmental agreement given that they cooperate in R&D subsidizing. Hence R&D subsidies stabilize the environmental agreement. The gain from the optimal joint R&D subsidy exceeds any gain from deviation from the cooperative behavior.

The paper gives an opportunity to consider the issue of the countries' asymmetry with respect to their gains from the international environmental agreement. An environmentally more conscious government induces others to enter the environmental agreement and choose socially efficient emission levels. It can be done via subsidies to the RJV between the firms of the participating countries. The subsidies induce a less conscious country to cooperate in the environmental agreement. Both countries gain from the subsidies to RJV between their firms[27].

The studies of Katsoulacos (1997) and Carraro and Sinescalco (1995, 1997) conclude that the linkage between the environmental cooperation and technological agreement leads to larger environmental coalitions. Tol et al. (2000)[28] basically confirms the findings that a country has less reason to free-ride if the free-riding implies that the country looses access to the desirable foreign technologies. They assume that the technological development is driven by the greenhouse gas emission reduction activity[29] and investigate whether the restrictions on the diffusion of the carbon-saving technologies can be a credible instrument in establishing more cooperation between the countries. They point out several limitations in using ITC to stabilize climate coalitions. First, in many cases it hurts coalition to deny access to its common technology for the deviator country if the deviator retaliates by withdrawing its technology or denying access to its innovation. If the deviator is large relative to the size of the coalition, the coalition bears high loss, and hence the threat to exclude the deviator from the technological coalition may not be credible. Second, carbon saving technology must be important for all countries regardless of the fact of their participation in the agreement. At the same time when a country drops out of the environmental agreement it becomes less concerned about the technology that reduces abatement costs. Hence the participating countries are interested in carbon-saving technology as long as they are interested in the climate coalition. These two effects reduce the loss of the deviation while the free-riding benefits remain the same. Thus they undermine the role of the induced technological

[27] It is worthwhile to note that firms would cooperate even without the subsidies but in this case they would choose suboptimal R&D and sharing parameters sub-optimally. Thus the welfare gain from the R&D subsidy is the surplus to the welfare in the non-cooperative R&D equilibrium.
[28] The novelty in Tol et al.(2000) is a dynamic approach.
[29] The ITC was modeled as LBD that reduces abatement costs and spreads to other countries via a diffusion process.

progress in integrating countries in the environmental coalition. The general conclusion is that the linkage of greenhouse gas emission reduction with technology diffusion has only modest success in managing the free-riding problem and only if the two issues are automatically linked.

Finally, several caveats for the practical implementation of the links can be named. First, patents, the means to protect from free diffusion, are routinely pirated. Second, not governments but companies hold the patents. Third, developing countries would gain most from emission abatement but they have the most inferior technology to offer. At the same time the USA is both a major developer of technology and reluctant to reduce the greenhouse gas emissions. Fourth, the threat of excluding the defector must be automatically exercised, but that is not the case in a real life.

6. Concluding remarks

International environmental cooperation is important to deal with the problem of increased greenhouse gas emissions in the atmosphere. A long-term character of the mitigation process makes it important to take into account possible technological changes: process and product innovations. At the same time, environmental policy shapes the technological development. In this overview I have considered the main streams in the literature that analyses the design of international environmental treaties in the presence of induced technological changes. In this section I mention some direction for further analysis within this field.

First, an international environmental agreement via induced technological changes affects energy prices. It has an impact on the strategic interests of separate countries (e.g., oil and gas exporters and importers). These interests affect the choice of instruments and the sustainability of the environmental coalition. To my knowledge, there has been no thorough analysis of this problem.

The second perspective for further research is to integrate an international approach with a firm-level one. The main part of abatement and environmental R&D is done by the private sector. Incorporation of the results made for firm-level studies into the analysis of the international policy is a promising direction for research[30].

One of the features of technological innovations is the uncertainty of their success and their eventual effect on abatement costs. The uncertainty with respect to technological changes, other governments' actions and the future emission level introduces noises even in a well-designed international policy. Thus it is necessary to analyse how the policy instruments should be constructed to address the global environmental problem under these conditions.

[30]So far this approach was implicitly applied in the papers that analyze emission taxes. E.g., in addition to the case when countries act as agents and choose their abatement level and R&D, Hoel and Golombek (2002) consider the case when the government does not choose the abatement level, but affects it via domestic taxes.

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Appendix: A brief overview of national level studies

Here I make a brief overview of firm- and industrial-level studies of environmental policy instruments in the presence of ITC. A huge part of innovations is made within a private sector. When a government chooses environmental policy instruments to meet an international target, the choice affects innovative and adoptive behavior of the private sector. In addition, an international treaty may be supplemented by direct prescriptions/recommendations to participating countries with respect to their domestic policy. The overview is aimed to help to provide some recommendations for the optimal domestic environmental policy.

Comparison of policy instruments in the presence of ITC

The main theoretical finding is that despite the same amount of emission reduction, different policy instruments provide firms (countries) with different incentives for their R&D activity (e.g., Fischer et al. 1998). However, the difference matters only if the policies are not revised over the considered period. Frequent adjustments eliminate the difference but may cause high administrative costs (see Montero, 1998). In addition, frequent corrections reduce the private sector's trust in the environmental policy.

There are two major effects that have an influence on the firms' innovation behavior. The first one is a direct – a reduction of marginal abatement costs caused by innovation of new technology. The second indirect effect is the influence of innovation on emission payment. This effect implies i) a reduction of the emission amount to be paid for (especially strong in the case of the emission tax) and ii) a reduction of the price of permits (crucial for tradable emission quotas and especially strong in the auctioned case).

Fischer et al. (1998) analyze different policy instruments with respect to their influence on the innovative and adoptive behavior of firms. The analysis was made for the following framework. There are a number of identical firms in the economy. One of them invests in R&D to develop a new technology that reduces marginal abatement costs. In the next stage non-innovating firms decide whether to adopt the new technology. To get the right for the adoption they have to pay a royalty to the innovator. Perfect competition is assumed on the emission market. In addition to the two effects mentioned above there arises an adoption price effect: since the innovation reduces the price of permits, non-innovating firms are less eager to pay for the adoption of a new technology. The effect works in the opposite direction to the two previous effects.

The theoretical model and consequent simulations show that the ranking of the policies with respect to a welfare improvement depends on the relative importance of the highlighted effects[31]. The strength of the effects is stipulated by the following parameters: an ability to imitate the innovation, costs of innovation[32], a shape of an environmental benefit function and the number of emitting firms.

The theoretical model demonstrates that whether innovation incentives are highest under the emission tax (fixed tax is considered) or auctioned permits is ambiguous. It depends crucially on the imitation ability. If there are no spillovers (i.e. a firm captures the whole rent from its innovation), a tax provides greater innovation efforts. The reason is that under the policy of tradable permits the reduction of abatement costs is applied to a fixed amount of abatement, while under the tax the effect is applied to the increased amount of abatement. With the increasing ability to imitate a new technology, tradable emission permits provide more innovation. In the case of perfect imitation, a tax does not allow an innovator to capture the gain from the other firms' emission reduction. In the case of tradable emission permits, the imitation of the new technology contributes to technological diffusion and reduces the emission price. Thus, the innovator is partly compensated. Auctioned permits produce more innovation than grandfathered because of the stronger emission payment effect[33]. As a rule the abatement effect is weaker and the royalty payment received from non-innovators is smaller for the grandfathered permits than for the emission tax.

Parry (2001) points out that the relative advantage of the tax depends on the amount of abatement / or the initial abatement level. The tax is a preferable instrument when it produces higher abatement amounts or when the initial abatement level is low. The advantage disappears when the innovation produces a moderate reduction of the abatement costs.

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[31] Under competitive settings (when firms are price-takers) and in the absence of R&D-spillovers all four instruments (emission standards, grandfathered marketable permits, auctioned permits, taxes and subsidies) provide the same incentives given that all the instruments are constantly revised and result in an equal aggregate emission reduction (see Montero 1998, Parry 2001)

[32] Higher costs of R&D counteracts the abatement cost effect and reduce the abatement level and hence reduce the advantage of a tax policy.

With a small number of firms on the permit market, the amount of innovation is significantly higher under the auctioned permits. In this case innovations help firms to exercise their ability to reduce the price of permits.[34] With the large number of firms an additional argument in favor of the tax is a strong negative spillover effect in the case of tradable permits (see Montero, 1998) since the innovator does not appropriate the gains of other firms from the reduced permit price.

The innovation is costly and socially desirable only if its marginal gain exceeds marginal costs. The welfare ranking of the policy instruments is even more ambiguous than the ranking with respect to their ability to induce innovations. The welfare ranking depends on which policy induces abatement and innovations closer to the first-best levels. The slope of marginal environmental benefits becomes a very important parameter in the ranking procedure. Let us consider first the case of constant marginal environmental benefits. The imitation ability makes a private gain from the innovation smaller than the social one. The emission tax that is equal to the marginal emission benefits provides a correct level of abatement. At the same time, the innovation level is lower because of the imitation effect. Free permits increase the divergence between the private and social amount of innovation. In addition, tradable quotas preclude an adjustment of the abatement level when marginal abatement costs fall. Welfare is unambiguously lower in the free tradable permit case. According to the simulations, the welfare gain is typically lower under auctioned permits then under the tax. The exception is the case when the innovation is greater under auctioned permits than under the emission tax, and the welfare gain from this extra innovation more than outweighs the welfare loss from the sub-optimal abatement level.

When marginal environmental benefits decline, then a tax which is initially equal to the Pigovian level results in excessive abatement when innovation drives marginal abatement costs down. As a result, the rigid tax level results in a socially excessive abatement level. In addition, with a tax innovation may exceed a first-best amount: if the abatement cost effect more than outweighs the negative imitation effect the demand for

[33] See Montero (1998) and Parry (2001).

[34] It holds only if a firm innovates and appropriates the gain from innovation. An external innovator cannot capture the benefits from the lower price and the innovation level for grandfathered and auctioned permits will be the same.

innovation will increase. With grandfathered tradable quota innovations are below the socially optimal amount. This is a result of the imitation. Auctioned permits produce insufficient innovation as well.[35]

If the slope of the marginal environmental benefit curve is steep, then the permits are better than taxes in addressing the innovation since the permits better suit the direction of the change in marginal abatement costs (the result is based on the Weitzman (1974) approach).

The above results may be extended for the case when all firms have a possibility to innovate (see Parry, 2001). Fischer (2000) considers the influence of different policy instruments on technological changes separately for their two stages: innovation and adoption. The findings are summarized in the table 1.

Table l: Incentives for innovation and adoption created by policy instruments.[36]

Policy instrument	*Direct gain for innovating firm*	*Potential rents from adoption*
Best-Available Technology	- *new standard raises overall compliance costs*	+++ *tighter standard raises incentives to adopt*
Performance standards	++ *to reduce existing abatement costs*	++ *limited to the existing abatement costs*
Emission tax	+++ *lowers abatement costs and taxed emissions*	+++ *lowers abatement costs and taxed emissions*
Auctioned Emission permits	++++ *lowers abatement costs and costs of all permits purchased*	+ *buying permits becomes a cheaper alternative*
Grandfathered Emission permits	++ *lowers abatement costs*	+ *buying permits becomes a cheaper alternative*
Tradable performance standards/ Output-Allocated permits	++ *initial abatement costs higher but lowers output subsidy*	++ *initial abatement costs higher but permits become cheaper*

It is believed that market-based instruments not only promote a cost-efficiency but also provide the most efficient incentives for the development of environmental-friendly technologies (e.g., see Table 1). For certain conditions however a command-and-control instrument such as emission standards[37] [38] may provide greater incentives for

[35] An exception is the case of a strong emission payment effect.
[36] The greater the number of plus signs the higher incentives are provided by the policy instrument.
[37] Dictate certain emission level of abatement but leave the methods up to the firm.
[38] The reasoning is true for emission standards, not technology-based standards. The latter kind of command-and-control instruments hardly provides any innovation incentives.

innovation than taxes or permits. For example, Montero (1998) points out certain aspects that make the command-and-control policy a superior one in the innovation inducement. One reason is that the imitation possibility[39] undermines the innovative incentives of market-based instruments. The other reason is a convexity of the abatement cost function in the emission reduction level. Thus a reduction of marginal abatement costs induced by R&D is more valuable for a higher abatement level. If emission standards are set far from their least-cost allocation, the innovation produces greater cost savings. The advantage of the emission standards disappears when innovation opportunities differ across firms or the initial allocation is not too far from the least-cost one. However, the work lacks the comparison of the policy instruments with respect to their effect on welfare.

Thus the ranking of policy instruments depends on the particular features of the innovation and adoption processes.

Environmental policy versus direct instruments in stimulating environmental R&D

Parry (2001) claims that it is more efficient to use direct instruments (e.g., government R&D, R&D-subsidies, research tax credits) for stimulating research rather then trying to induce environmental R&D via tightening the environmental regulation, the primary aim of which is a pollution reduction[40]. The reason is that a stricter environmental policy not only creates incentives to innovate but leads to too much abatement as well. An additional problem here is the difficulty of an ex-ante assessment of the innovation effect.

Parry et al. (2000) and Fischer (2000) divide the welfare gain of the environmental policy into two welfare gains. One is the gain from achieving a socially optimal innovation path of cleaner technologies induced by the policy. Another is the gain from the environmental improvement - so-called “Pigovian” welfare gain (technology held constant). Parry et al. (2000) and Fischer (2000) show that the first innovation gain is significantly less than the “Pigovian” one. The two effects are

[39] Actually, there are two imperfections in the research market. First, there is a positive spillover effect to other firms if they can copy or imitate the innovation. The effect works in the direction of too little R&D. Second is an opposite effect - “common pool”(business stealing). The success of one firm lowers the likelihood for other firms to obtain innovation rents. Empirical evidence from commercial (non-environmental) innovations indicates that the first effect outweighs the second one. Hence, in general, the social rate of return on innovation is higher than the private one (see Cohen and Noll, 1994).

[40] For environmental tax this result was proved in Parry (1995).

compatible only if the initial abatement is low. In this case innovations that reduce the costs of abatement give higher gain. It is also true for the cases when innovations lead to a fast reduction of abatement costs; or when there is a low discount rate, or low costs of R&D. However, in general, the gain from innovation is small comparative to environmental gains.

However the result was obtained for the first-best world where innovation opportunity was considered for the optimal level of pollution reduction (i.e. was added to the first-best "Pigovian" gain). There is a possibility that the result changes for the second-best case. For example, if there is a pre-existing sub-optimal lower pollution control and the innovation helps to reach the optimal pollution control level, the value of innovation should be extended by the gain from the pollution correction. The analysis of Parry et al. (2000) and Fischer (2000) does not take into account technological positive spillovers from environmental R&D to the other sectors. The last aspect, missing in the analysis, is an overestimation of the "Pigovian" gain because of the omitted increase of product prices, distortions from the pre-existing taxes on factor markets (see Goulder et al. 1999). Thus the ability of the innovation to soften the negative effects augments its relative gain. In general, one has to assess all the gains and losses of the induced innovation.

Impact of the environmental policy on R&D in the whole economy

It is quite unlikely that there is an underemployed pool of knowledge in the economy. With an inelastic supply of R&D-activities the environmental R&D reduces innovation in other industries. This distortion effect reduces the innovation gain from the environmental policy. The usual tool for analysis of the R&D-distortion is a top-down multi-sector computable general equilibrium model (e.g., Goulder and Schneider 1999, Kverndokk et al. 2001, Rasmussen 2001).

Goulder and Schneider (1999) consider profit-maximizing R&D-investments induced by a carbon emission abatement policy (in particular, a carbon tax) and analyze the R&D-reallocation among different sectors. The economy is divided into three aggregate sectors: an alternative energy industry, a conventional fuel industry and a non-energy industry. The main findings are the following. The fuel tax encourages R&D in the alternative energy sector. At the same time, an expected fall in the demand in the conventional sector reduces R&D-activity in this sector. An overall drop in incomes causes a fall in demand in the non-energy industry. The demand contraction, together with the increased prices of the energy intensive materials, decrease R&D in the non-energy industry. The resulting effect is a fall of aggregate expenditures on R&D that affects GDP-growth adversely.

The emission tax reallocates R&D from the conventional to the alternative industry. The opportunity costs of the tax depend on the inefficiencies in the R&D market and pre-existing subsidies on R&D. The social value of R&D is greater for an industry with high knowledge spillovers. The higher spillovers in the alternative sector, the lower are the opportunity costs of the R&D-relocation imposed by the carbon tax. Thus knowledge spillovers justify subsidies to R&D[41]. Pre-subsidies to R&D in the alternative sector make innovations in the conventional industry less efficient relative to innovations in the alternative sector. Hence the pre-subsidies increase the costs of the R&D-relocation caused by the tax.

It was mentioned in Goulder and Schneider (1999) that similar results may be obtained for technological changes in the form of LBD. In this case the analysis should take into account that a conventional industry is mature and its LBD ability is relatively smaller. The sample of the analysis is a work of Rasmussen (2001) made for Denmark. Rasmussen (2001) exaggerates the difference in LBD among the energy-producing sectors and assumes that only the renewable energy sector experiences LBD. ITC in renewable energy reduces marginal and total abatement costs. With LBD, demand for renewable energy stimulates technological progress. The effect is modest initially when the level of technological improvement is low, but becomes substantial when more abatement is performed. Simulations show that the effect of the cheaper future abatement outweighs the positive LBD-effect of an earlier abatement. It is a result of the technological progress[42] in the presence of banking option (i.e. when the emission restrictions are set for the long-run period rather than for a sequence of short-run time

[41] It is worthwhile to note that it is not the presence of ITC, but the presence of knowledge spillovers, which justifies the subsidies. It was shown that the subsidies to R&D increase the mitigation costs in the absence of knowledge spillovers.

[42] The effect is reinforced here by the effect of the falling price of capital services on the return to investments in renewable energy.

intervals, that give an opportunity to vary abatement within the period). Hence there is less near-term abatement[43] and emission path moves closer to the present.

Positive knowledge externalities cause a near-term abatement to be less in a market scenario than in the socially optimum scenario. Subsidies to production of renewable energy capital are a more direct way to address the inefficiency. However, the large subsidy causes an over-provision of the renewable energy. The effect increases with the level of output. In the presence of subsidies it is thus optimal to postpone emissions to the future and slow the expansion of the renewable energy. An additional factor that favors the delay in the optimal emission path is existing distortion in the tax structure. The distortion increases the alternative costs of the subsidy. Both effects are absent in a market scenario. The simulation analysis shows that in the presence of LBD a subsidy drives the market emission level down less than an optimal emission path. It increases the divergence between the optimal and market emission paths and decreases welfare.

Kverndokk et al. (2001) add to the model the possibility of the appearance of an entirely different new technology (while in Goulder and Schneider (1999) the alternative technology is gradually developing). The comparison of a carbon tax and subsidizing of an alternative technology reveals the superior performance of the uniform carbon tax.[44] [45] There are several reasons for this. First, the government may not correctly predict what technology will appear on the market after the restrictions are placed on fossil fuel use. Second, there are positive spillovers created by energy production based on the new technology. Subsidizing an existing alternative technology may delay the development of a new and more efficient one. Rigidity of the real political instruments[46] enhances the result. In this sense taxes are more neutral in encouraging the new carbon-free technology than subsidies.

In the bottom line, it is important to mention that an ideal policy should take into account future innovations and their impact on the costs and benefits of the implemented policy.

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[43] The result is consistent with Goulder and Mathai (2000)
[44] Even the presence of positive spillovers in the alternative non-polluting technology does not change the result.
[45] The ranking was made according to a welfare-maximization criterion.
[46] For example, long way to impose, remove and redirect subsidies.

One of the main sources of difficulty in designing an optimal policy is uncertainty in the success of R&D investment[47]. The uncertainty of abatement costs makes policy instruments unequal in their efficiency to deal with the environmental problem. In these conditions policymakers need to weigh the benefits and costs of inducing more or less innovation against too much and too little abatement. A fixed tax policy does not allow emission prices to adjust, thus creating a risk of too much abatement if costs fall[48]. However, taxes do allow the amount of abatement to fluctuate according to cost conditions. On the other hand, a permit policy does not allow a quantity adjustment of abatement, meaning that too little will be done if the costs fall (and too much effort will be put into abatement if costs rise).

In the case of greenhouse gas emissions, their potential damage is relatively insensitive to the rate of emissions at any particular time[49]. It favors a tax-based approach over a quantity-based permit approach. The reason is that in these circumstances the uncertainty about the volume of abatement imposes less of burden on society than does the abatement cost uncertainty (an empirical evidence is found in Pizer (1999), Newell and Pizer (1999), Hoel and Karp (2001, 2002).

It was shown that a technology-aimed policy is not a substitute for the environmental-aimed one. The primary gains to environmental protection come from reduction of the environmental damages in the most cost-effective manner. These gains are higher than the ones obtained from the induced innovations. Too much concern about the effect on technology leads to too much spending on R&D and structural distortions of R&D activity.

Of course, one-country studies miss several important aspects. For example, there are technological changes in other countries that change energy prices in the world market and demand for renewable domestic energy. There may be positive international technological spillovers that affect domestic technological changes (see part 3). These aspects are analyzed by means of the international approach.

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[47]It is a result of uncertainty of the evolution of new technology (since it is affected by other factors, e.g., changes in energy prices), uncertainty of an uncontrolled emission level.
[48] Assuming the tax starts out from the initial damage costs of emissions.
[49] Although the total cost will likely rise as greenhouse gases accumulate in the atmosphere

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