The Optimal Climate Policy Portfolio when Knowledge Spills across Sectors

Emanuele Massetti
Lea Nicita

CESIFO WORKING PAPER NO. 2988
CATEGORY 10: ENERGY AND CLIMATE ECONOMICS
MARCH 2010

PRESENTED AT CESIFO AREA CONFERENCE ON ENERGY & CLIMATE ECONOMICS, OCTOBER 2009

CESifo *Working Paper No. 2988*

The Optimal Climate Policy Portfolio when Knowledge Spills across Sectors

Abstract

This paper studies the implications for climate policy of the interactions between environmental and knowledge externalities. Using a numerical analysis performed with the hybrid integrated assessment model WITCH, extended to include mutual spillovers between the energy and the non-energy sector, we show that the combination between environmental and knowledge externalities provides a strong rationale for implementing a portfolio of policies for both emissions reduction and the internalisation of knowledge externalities. Moreover, we show that implementing technology policy as a substitute for stabilisation policy is likely to increase global emissions.

JEL-Code: C72, H23, Q25, Q28, O31, O41, Q54.

Keywords: technical change, climate change, development, innovation, spillovers.

Emanuele Massetti
Fondazione Eni Enrico Mattei
Corso Magenta, 63
Italy - 20123 Milan
emanuele.massett@feem.it

Lea Nicita
Fondazione Eni Enrico Mattei
Campo S. Maria Formosa
Castello 5252
Italy – 30122 Venice
lea.nicita@feem.it

March 2010
This paper is part of the research work being carried out by the Sustainable Development Programme at the Fondazione Eni Enrico Mattei and by the Climate Impacts and Policy Division of the Euro-Mediterranean Center on Climate Change. Financial support from the Italian Ministry of the Environment and the PASHMINA project is gratefully acknowledged. The authors are grateful to Carlo Carraro for useful comments and remarks. An earlier version of the paper titled “Optimal R&D Investments and the Cost of GHG Stabilization when Knowledge Spills across Sectors”. The authors are also grateful to participants at the CESifo Conference on Energy and Climate Economics, in particular to Michael Hoel and Reyer Gerlagh.

1. Introduction

There is now a wide agreement that any stringent policy to reduce the concentration of atmospheric concentrations of Greenhouse Gases (GHGs) will call for a tremendous effort in technological innovation. Therefore, at the frontier of climate and energy modelling research we find the study of innovation dynamics. During the last decade the description of technical change in integrated models for climate policy analysis has greatly improved.[1] However, current approaches still omit important elements that affect the dynamics of technical change and a broader framework for analysing technical change is advocated. In particular, knowledge externalities, although pervasive and extremely relevant in shaping innovation dynamics, are usually not modelled.

The presence of market failures in the R&D sector, as emphasized by Griliches (1957, 1992), is confirmed by the evidence, virtually found in all studies, that the social rate of return on R&D expenditure is higher than the corresponding private rate[2]: estimates of the marginal social rate of return to R&D investment range between 30 and 50 percent and of private return between 7 and 15 percent.

Spillovers are generally acknowledged as a fundamental aspect of technical change. The new growth theory that has followed the seminal work of Romer (1990), has emphasised the importance of international R&D knowledge spillovers (Grossman and Helpman, 1991, chs.11 and 12), and of both *intra*sectoral and *inter*sectoral R&D knowledge spillovers in explaining countries' productivity (Jones, 1999; Li, 2000). Those contributions have stimulated the development of a number of studies that estimate the importance of R&D spillovers among firms, sectors or countries.[3] Overall, the available empirical evidence supports the idea that spillover effects are relevant and positive, even if, due to the variety of methodologies used, estimates span over a wide range and their significance varies across studies.

When it comes to technologies for carbon emissions reduction, the difference between private and social rate of return to R&D investment arises from a double externality: the presence of both environmental and knowledge externalities. First, without a price on carbon that equates the global and the private cost of emitting GHGs, all low emissions technologies are relatively

[1] See Gillingham et al. (2008) for a recent overview of modelling methodology.
[2] Among others Mansfield (1977, 1996), Jaffe (1986), Hall (1996), and Jones and Williams (1998).
[3] An extensive review of the literature on spillovers at firm level can be found in Wieser (2005). Keller (2004) reviews a large part of the literature on international spillovers.

disadvantaged and the level of investment is therefore sub-optimal. Second, the private return to investment in R&D is lower than the social return of investment due to the incomplete appropriability of knowledge creation, thus pushing further away investments from the socially optimal level.[4]

Many researchers that have worked on the optimal design of climate policy have stressed the importance of studying climate policy in a second-best setting considering the double externality. For example, Jaffe et al. (2005) proposes to use a portfolio made of a price signal to correct for the environmental externality coupled with a policy to support investment in technologies to reduce GHG emissions. The idea of complementing a stabilisation policy with an R&D policy in order to address both externalities at once is instead opposed by Nordhaus (2009). He argues that once the environmental externality is corrected, there are no evident reasons to treat research in technologies to reduce GHG emissions differently from other kinds of research that share the same characteristic of public good.

These doubts recently raised by Nordhaus (2009) clearly show that we are far from understanding the optimal policy mix that reduces effectively and efficiently global warming and climate change. This paper contributes to the literature by providing answers to three sets of major policy questions using a sophisticated modelling environment in which it is possible to study both the environmental and the knowledge externality.

These three sets of policy questions are the following. First, what is the optimal response, in terms of investments in R&D (both in energy and non-energy technologies) of a policy to stabilise the atmospheric concentrations of GHGs, when domestic intersectoral knowledge spillovers are explicitly modelled? Can we expect that the stabilisation policy will drive the economies closer to or farther from the socially optimal level of innovation? Second, what would be the optimal amount of R&D spending and what would be the environmental consequences of correcting only knowledge externalities? Third, what are the welfare implications of addressing both environmental and knowledge externalities with a policy mix that combines a stabilisation policy and R&D policies to support the optimal level of innovation?

To provide an answer to these questions we have up-graded the hybrid Integrated Assessment Model WITCH model by introducing knowledge spillovers between R&D investments to increase energy efficiency (energy sector) and investments in knowledge creation to increase the

[4] For an introduction to the literature on the double externality see Nordhaus (1990).

productivity of the capital-labour aggregate (non-energy sector). We build upon previous work in which knowledge dynamics of the WITCH model have been enriched by introducing directed technical change in energy and non-energy inputs (Carraro, Massetti and Nicita, 2009) and we abstract from international spillovers, which, as we show in a previous paper (Bosetti *et al*, 2008), have a modest role in shaping innovation dynamics.

Our work represents a pioneer attempt to introduce *inter*sectoral spillovers in a complex Integrated Assessment Model (IAM). IAMs typically do not explicitly describe market failures. Until now, the few attempts to incorporate R&D spillovers in integrated models for the study of climate policy have been confined to the inclusion of *intra*sectoral spillovers (Popp, 2006), and international spillovers (e.g. Bosetti *et al*, 2008). However, empirical studies provide evidence that *inter*sectoral spillovers are extremely significant, as claimed by Wieser (2005) in his broad review of the literature. Without *inter*sectoral spillovers, models unrealistically assume that the advance of technological frontiers of different sectors is mutually independent, omitting the interactions among the different drivers of technical change.

By describing endogenous knowledge development dynamics in a second-best world, we are able to produce insights on the widely debated question of the optimal portfolio of climate policies. Moreover, our numerical assessments give quantitative foundations to a debate that has been theoretical and not grounded on empirical basis so far.

Goulder and Schneider (1997) and Popp (2006) are the two main studies that analyse by means of computational models with knowledge externalities a climate policy portfolio in which R&D policy is coupled with a policy to reduce GHG emissions. However, there are major differences among modelling assumptions that allow only marginal comparisons of results. First and foremost Goulder and Schneider (1997) and Popp (2006) concentrate only on *intra*sectoral spillovers. The WITCH model displays *intra*sectoral spillovers and in principle it is possible to replicate the analysis of the earlier studies. We assume, however, that the *intra*sectoral inefficiencies in knowledge creation are fully internalised and we instead concentrate on *inter*sectoral spillovers to incorporate the complex interaction of R&D dynamics between two broad sectors that are affected differently by a policy to reduce GHG emissions. A further difference with respect to Popp (2006) is that we do not exogenously impose that increased spending in energy R&D crowds-out other kinds of R&D investments. By modelling endogenous knowledge accumulation in the two knowledge stocks, we can describe the optimal reallocation of resources to R&D in general, and between sectors. Our conclusions depart in a number of ways from those of previous studies, as we explain in the following.

Our analysis is both oriented to answer policy questions and to discuss modelling issues. We aim to provide useful insights both to policy analysts and to the community of modellers.

Section 2 briefly describes the model and Section 3 presents calibration details. Section 4 describes the basic features of the Business as Usual scenario (BaU) and introduces historical evidence on R&D patterns. Section 5 examines how incentives to invest in different kinds of R&D are changed by a policy whose aim is to correct the global environmental externality that arises from GHGs emissions. Section 6 explores the problem from the opposite angle and we look at the implications for the environment of solving the sole knowledge externality. Section 7 studies the welfare implications of addressing both externalities. Finally, Section 8 introduces the results of the sensitivity analysis. We conclude by assessing our results against earlier findings in the literature, drawing policy implications and suggesting some patterns for further research.

2. Model Description

2.1 Short model description

WITCH (World Induced Technical Change Hybrid) is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate damages (Bosetti *et al.* 2006, 2009b; Bosetti, Massetti and Tavoni, 2007).

It is a hybrid model because it combines features of both top-down and bottom-up modelling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up like description of the energy sector. WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

World countries are aggregated in twelve regions on the basis of geographic, economic and technological vicinity (see Footnote 18 for a list of regions) which interact strategically on global externalities: greenhouse gases, technological spillovers, and a common pool of exhaustible natural resources.

WITCH contains a detailed representation of the energy sector, which allows the model to produce a reasonable characterisation of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilising greenhouse gases concentrations. In addition, by endogenously modelling fuel prices (oil, coal, natural gas, uranium), as well as the cost of storing the CO_2 captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

In WITCH, emissions arise from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomasses and soils. Emissions of CH_4, N_2O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO_2 aerosols, which have a cooling effect on temperature, are also identified. Since most of these gases are determined by agricultural practices, the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves.[5]

A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHGs concentrations. WITCH is also equipped with a damage function that provides the feedback on the economy of global warming. However, in this study we do not take a cost-benefit approach. We work in a "cost-minimisation" framework: with a given target in terms of GHGs concentrations in the atmosphere, we produce scenarios that minimise the cost of achieving this target.

Endogenous technological dynamics are a key feature of WITCH. Dedicated R&D investments increase the knowledge stock that governs energy efficiency. Learning-by-doing curves are used to model cost dynamics for wind and solar capital costs. Both energy-efficiency R&D and learning exhibit international spillovers. There are two backstop technologies: one in the electricity sector and the other in the non-electricity sector. They necessitate dedicated innovation investments to become competitive. In line with the most recent literature, the costs of these backstop technologies are modelled through a so-called two-factor learning curve, in which their price declines with investments in both dedicated R&D and technology diffusion.

2.2 Directed Technical Change with Intersectoral Spillovers

Gross output, $GY(n,t)$,[6] in region n at time t is produced by combining energy services, $ES(n,t)$, and capital-labour services $KLS(n,t)$ in a constant elasticity of substitution (CES)

---

[5] Reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH includes a baseline projection of land use CO_2 emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission trading system and have the capacity to implement REDD programs. However, avoided deforestation is not a source of emissions reductions in the version of the model that we used for this study.

[6] Net output, $Y(n,t)$, is obtained after accounting for the effects of climate change on production and the expenditure for fuels and carbon capture and sequestration, as shown in the Appendix.

nest:[7]

$$GY(n,t) = TFP(n,t)\left[\alpha_Y(n) \cdot KLS^{\rho_Y} + (1-\alpha_Y(n)) \cdot ES(n,t)^{\rho_Y} \right]^{1/\rho_Y} \quad (1)$$

Energy services and capital-labour services are obtained by aggregating capital-labour and energy inputs with knowledge, which raises the productivity of raw inputs. As a proxy of knowledge we use the cumulated stocks of R&D in the non-energy and energy sectors, $HKL(n,t)$ and $HE(n,t)$, respectively. The aggregation between raw inputs and knowledge is assumed to follow a standard CES function:

$$ES(n,t) = \left[\alpha_{ES}(n) HE(n,t)^{\rho_{ES}} + (1-\alpha_{ES}(n)) EN(n,t)^{\rho_{ES}} \right]^{1/\rho_{ES}} \quad (2)$$

$$KLS(n,t) = \left[\alpha_{KLS}(n) HKL(n,t)^{\rho_{KLS}} + (1-\alpha_{KLS}(n)) KL(n,t)^{\rho_{KLS}} \right]^{1/\rho_{KLS}} \quad (3)$$

Calibration details are discussed in Section 3. The energy input $EN(n,t)$, is produced in the energy sector of the economy, and we refer to Bosetti, Massetti and Tavoni (2007) for a more detailed description. It basically consists of a series of nested CES functions that describe energy supply and demand at different levels of aggregation. Capital and labour are aggregated in a CES nest to produce the capital-labour raw input *KL* as follows:

$$KL(n,t) = \left[\alpha_{KL}(n) K_C(n,t)^{\rho_{KL}} + (1-\alpha_{KL}(n)) L(n,t)^{\rho_{KL}} \right]^{1/\rho_{KL}} \quad (4)$$

This formulation is supported by empirical evidence, as explained in Carraro, Massetti and Nicita (2009).[8]

2.3 The R&D Sectors

The stocks of knowledge that each region can use to increase the productivity of capital-labour and energy inputs is accrued by means of investments in R&D which are in turn enhanced by knowledge spillovers. We account for two different types of knowledge spillovers. First, knowledge is produced by standing on the shoulders of one nation's giants: investment in R&D is combined with the stock of ideas already discovered and produces new knowledge which will be the base for new discoveries in the following years (Romer, 1990; Jones, 1995; Popp, 2004). These can be seen as intertemporal spillovers or, from another perspective, as *intra*sectoral, lagged spillovers. Second, with this study we introduce *inter*sectoral knowledge spillovers by

[7] Where $\rho = (\sigma - 1)/\sigma$ and σ is the elasticity of substitution.
[8] See, among others: van der Werf (2007) and Chang (1994).

including among the inputs of the idea generating process in one sector of knowledge accumulated in the other sector. Accordingly, the production of new ideas, $Z\left(n,t\right)$, in the energy and non-energy sectors is modelled as follows:

$$Z_{HE}\left(n,t\right) = a\, I_{HE}(n,t)^{b}\, HE(n,t)^{c}\, HKL(n,t)^{d}\,, \tag{5}$$

$$Z_{HKL}\left(n,t\right) = f\, I_{HKL}(n,t)^{g}\, HKL(n,t)^{h}\, HE(n,t)^{i}\,. \tag{6}$$

Where $b+c+d<1$ and $g+h+i<1$. We assume that obsolescence makes a fraction δ of past ideas not fruitful for the purpose of current innovation activity. As a consequence, the stocks of knowledge evolve according to the following law of motion:

$$HE(n,t+1) = HE(n,t)(1-\delta)+Z_{HE}\left(n,t\right) \tag{7}$$

$$HKL(n,t+1) = HKL(n,t)(1-\delta)+Z_{HKL}\left(n,t\right) \tag{8}$$

The decision variables of the model are the investments in physical capital (for all different technologies in the energy sector and for the domestic capital stock), the two types of R&D investments and fuels expenditures for non-electric energy. As a consequence, the decision to invest in energy R&D and non-energy R&D, and therefore total R&D, is endogenous. It is optimally derived in each region by solving a dynamic open-loop game, which leads to a Nash equilibrium.

We can either solve the model assuming that knowledge spillovers are an externality, which the social planner that governs the economy is not able to control, or we can assume that society fully internalises knowledge externalities and chooses the optimal path of R&D investments accordingly. Our baseline scenario is constructed with the hypothesis that intertemporal (or *intra*sectoral) spillovers are fully internalised while knowledge spills across sectors as an externality. With this set-up we reproduce the sub-optimal investment in knowledge due to intersectoral spillovers. We increase the realism of the model and introduce the possibility to study climate policy in a second-best setting at regional level. This is not frequent in IAMs.

3. Calibration

We depart from the standard version of the model[9] and we adopt the same nesting structure of the production function as in Carraro, Massetti and Nicita (2009), which introduce directed technical change in WITCH. The elasticity between energy and capital-labour services, σ_Y , is set equal to 0.5 . The elasticity of substitution between labour and capital, σ_{KL} , is equal to 0.8 for all regions with the exceptions of China and South Asia, for which we allow a greater elasticity of substitution (σ_{KL} equal to 0.85). The elasticity of substitution between energy and energy knowledge, σ_{ES} , is set equal to 1.67, and the same value is used for the elasticity between capital-labour and non-energy knowledge, σ_{KLS} . For a detailed description of empirical evidence supporting the chosen structure and parameters values we refer to Carraro, Massetti and Nicita (2009).

The innovation possibility frontier has been calibrated for both the energy and the non-energy sector using data from the empirical literature and adjusting the productivity parameter to reproduce the R&D over GDP ratio at the base year (2005) and the dynamics observed in the past.[10] The initial stock of non-energy knowledge is built using the perpetual inventory model. The value of the elasticity of new knowledge creation with respect to intersectoral spillovers is set equal to 0.13. The choice of this value is based on the empirical work of Malerba, Mancuso and Montobbio (2007), which estimate a spillover-augmented knowledge production function analogous to the one we use in our work. They find that, at macro level, the elasticity of knowledge creation with respect to intersectoral spillovers is comprised between 0.11 and 0.20.

4. The Business as Usual Scenario

Our Business as Usual scenario (BaU) is obtained as an open-loop Nash equilibrium in which regions compete on the use of the environmental public good, on the use of fuels. A lagged, global, learning-by-doing process governs the cost of wind and solar power plants.[11]

---

[9] We use here the latest version of the model, WITCH08 as described in Bosetti et al (2009). In the latest version, the model was updated withrecent data and revised estimates for future projection of population, economic activity, energy consumptions and climate variables. The base calibration year has been set at 2005.

[10] For an alternative approach see Bosetti et al (2008).

[11] In Bosetti *et al* (2008) and in other versions of the model there are also international knowledge spillovers in the Energy R&D sector. In this study we do not include international knowledge spillovers

Table 1 summarises baseline trends of major variables and indicators of interest. Gross World Product (GWP) increases over the entire century, starting from 44 trillion in 2005. It reaches 365 trillions in 2100, an almost nine-fold expansion. Population is exogenous, it grows at a declining rate and reaches a plateau at the end of the century. Gains in energy efficiency explain the reduction of emissions per unit of output. However, the strong expansion of output, coupled with a slight increase in carbon intensity, offsets all efficiency gains and overall carbon emissions increase throughout the century. This leads to a more than two-fold expansion of GHGs concentrations in the atmosphere.

	2005	2025	2045	2065	2085	2100
GWP (Trillions, 2005 USD)	44.21	87.94	151.81	228.00	306.46	359.30
World Population (billions)	6.51	8.01	9.02	9.53	9.51	8.96
Energy Intensity of Output (EJ/USD)	9.69	7.09	5.25	4.09	3.37	3.00
Carbon Intensity of Primary Energy (GtonC/EJ)	0.0183	0.0190	0.0201	0.0212	0.0221	0.0221
Concentrations of GHG (ppmv)	427	506	624	756	888	980
Investment in final good capital(%GWP)	20.23	18.49	16.82	15.57	14.51	13.98
R&D expenditure (%GWP)	2.15	2.24	2.30	2.38	2.45	2.46
Non-energy R&D (%GWP)	2.13	2.22	2.28	2.36	2.43	2.44
Energy Efficiency R&D (%GWP)	0.0216	0.0189	0.0181	0.0240	0.0178	0.0174
Energy R&D (%Total Investment in R&D)	1.01	0.84	0.79	0.76	0.73	0.71

Table 1. Baseline trend of major variables.

The model features an increasing path of R&D expenditure, as share of GWP. The fraction of investment devoted to knowledge creation is increasing. The model features a slightly declining path of energy R&D as share of GWP, an increasing path of non-energy R&D as share of GWP, and a declining rate of energy to non-energy R&D investments, with a relative share of energy R&D over total R&D declining from 0.73% to 0.61%. This is mainly explained by the fact that fossil fuels tend to remain inexpensive in our baseline scenario and do not motivate energy efficiency expenditures.

The optimal R&D investment path is in line with the historical trends of aggregate R&D. Figure 1 shows both the historical levels and the optimal trend of total R&D over GWP at world level.

---

but we still have international technological spillovers by means of a world learning curve for wind and solar power plants.

Historic data feature a slightly increasing trend over the past 10 years, starting from 2% in 1996 and reaching 2.1% in 2005. The same trend is predicted in the baseline scenario, with total R&D over GDP increasing from 2.1% in 2005 to 2.5% at the end of the century.

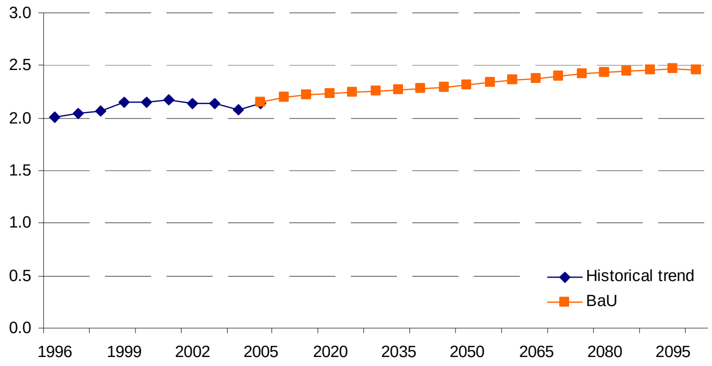

Figure 1. R&D as percentage of GWP.

5. Addressing the environmental externality: The Stabilisation Scenario

In this Section we explore how a policy to address the environmental externality only affects the rate and direction of technical progress when intersectoral spillovers between energy and non-energy R&D are modelled.

We correct the environmental externality by means of a policy to stabilise the level of GHGs concentration in the atmosphere. We construct a stabilisation scenario by imposing a cap on carbon emissions and by letting regions exchange carbon allowances on a global carbon market, which equates marginal abatement costs globally. We choose here a "Contraction and Convergence" allocation of carbon allowances.[12] The path of emissions that we impose leads to a stabilisation of CO_2 concentrations at 550ppm CO_2-eq target all GHGs included.

[12] With the "Contraction and Convergence" rule, permits are first distributed in proportion to present emissions and then the allocation progressively converges to an Equal-per-Capita allocation scheme, which becomes the allocation rule from 2050 onwards. In the Equal-per-Capita rule permits are distributed to regions in proportion to their population. Banking and borrowing of emissions allowances are not allowed, but there is no restriction to international trade of permits.

	2005	2025	2045	2065	2085	2100
GWP (Trillions, 2005 USD)	44.21	87.09	149.26	221.43	301.26	358.44
World Population (billions)	6.51	8.01	9.02	9.53	9.51	8.96
Energy Intensity of Output (EJ/USD)	9.69	5.98	3.47	2.37	2.08	2.00
Carbon Intensity of Primary Energy (GtonC/EJ)	0.0183	0.0157	0.0107	0.0071	0.0056	0.0048
Concentrations of GHG (ppmv)	427	491	533	548	550	552
Investment in final good capital(%GWP)	20.24	18.11	15.87	14.53	13.54	13.09
R&D expenditure (%GWP)	2.12	2.21	2.19	2.25	2.31	2.32
Non-energy R&D (%GWP)	2.09	2.14	2.13	2.19	2.25	2.27
Energy Efficiency R&D (%GWP)	0.0265	0.0304	0.0390	0.0740	0.0382	0.0356
Energy R&D (%Total Investment in R&D)	1.25	1.38	1.78	1.80	1.65	1.54

Table 2. Stabilisation trends of major variables.

Table 2 displays the trend of key economic variables when the stabilisation policy is implemented. The Gross World Product (GWP) over the whole optimisation interval 2005-2100 is lower than in the BaU scenario and discounted stabilisation policy costs are equivalent to 1.5% of BaU discounted GWP (using a 3% declining discount rate).[13]

The stabilisation policy has a remarkable impact on R&D dynamics, as the comparison between Table 1 and Table 2 clearly shows. First, it induces much higher spending in energy efficiency R&D, confirming results already established by a wide literature.[14] Second, the stabilisation policy induces a contraction of non-energy R&D spending, which is greater than the increase in energy efficiency R&D and thus determines an overall contraction of R&D activity.

Reduced spending in non-energy R&D is due to: (1) a general contraction of economic activity and (2) the fact that non-energy augmenting technical change is energy biased because of the complementarity between the energy and the non-energy sector. With energy biased technical change, an increase of non-energy R&D spending would increase energy use, and vice versa: by reducing non-energy R&D spending it is possible to reduce energy demand, an important way to cut emissions in a stabilisation scenario. It is therefore the stabilisation policy itself that

[13] The WITCH model uses an aggregate damage function to describe the feedback of temperature increase on GDP of each region. We thus account for the environmental benefits from the stabilisation policy. Costs rise because the stabilisation target imposed here is stricter than what found as optimal in a cost-benefit analysis with the WITCH model.

[14] See for example Bosetti et al (2009a) for an analysis with the WITCH model.

induces a contraction of the optimal level of R&D in the non-energy sector, and not the competition from higher spending in energy R&D. Carraro, Massetti and Nicita (2009) widely discussed this result and argued against the exogenous crowding-out hypothesis imposed in Nordhaus (2002) and Popp (2004, 2006) on the grounds that, at least in the medium/long term, societies are free to allocate the optimal amount of resources to knowledge creation. Recent empirical evidence presented in Newell and Popp (2009) confirms this intuition, showing that increased spending in energy R&D does not crowd out non-energy R&D.

By introducing a mutual link between the two knowledge frontiers, the stabilisation policy triggers more complicated dynamics of both energy and non-energy R&D investments (see equations 5 and 6). With respect to the model without intersectoral spillovers, the policy-induced positive shock to the stock of energy sector knowledge is transmitted to the non-energy sector. It increases the marginal return to non-energy R&D and partially offsets the contraction of R&D induced by the stabilisation policy. The final outcome is still a contraction of non-energy R&D greater than the increment in energy R&D, confirming the result that the stabilisation policy reduces knowledge accumulation even when endogenous spillovers are modelled.

It is now interesting to check how far the level of aggregate R&D spending in a stabilization policy is from the socially desirable one.[15] Figure 2 and

Figure 3 show the time path of R&D investments – as percentage of GWP – when the stabilisation policy is implemented and domestic knowledge externalities are internalised. The optimal path of energy R&D investments is characterised by a declining trend over the century. The converse is true for the optimal time path of non-energy R&D investments: the trend is increasing because the labour becomes a scarce resource as population growth levels off by mid-century. The difference between the optimal path and the second-best scenarios is striking. If we consider energy R&D, the stabilisation policy brings R&D investments closer to the socially optimal level. Remarkably, the jump from the level optimal in the BaU does not close the R&D gap. Contrary to what happens in energy R&D, the stabilisation policy brings investments in non-energy R&D. Consequently, total R&D investment moves farther away from the optimal level.

[15] Here we define an optimal world as one in which the stabilisation policy is implemented to correct the environmental externality and knowledge intersectoral externalities that are fully internalised in each region. This should not be confused with the global optimum, because we do not internalise other international externalities – e.g. on non-renewable resources use – and it is also not precisely a regional optimum, because the stabilisation policy is designed by a global social planner.

When only the environmental externality is addressed, there is ample space for R&D policies that correct the knowledge externality in both sectors, jointly or separately. In Section 7 we study the welfare implications of addressing both externalities. In the next section we address how the sole knowledge externality affects the environmental externality.

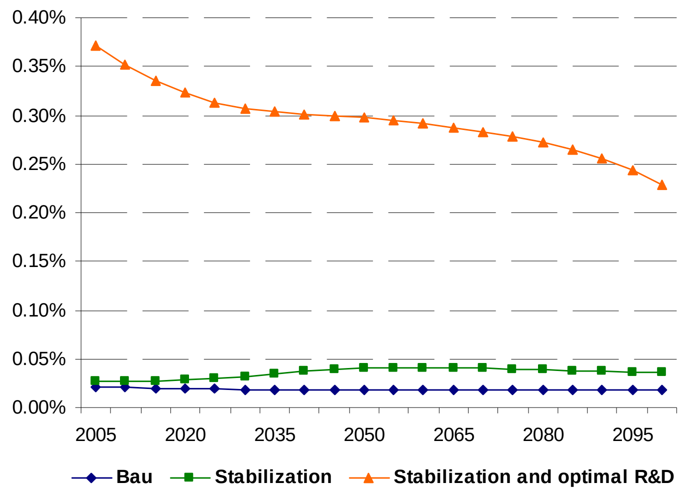

Figure 2. Investments in energy R&D/GWP.

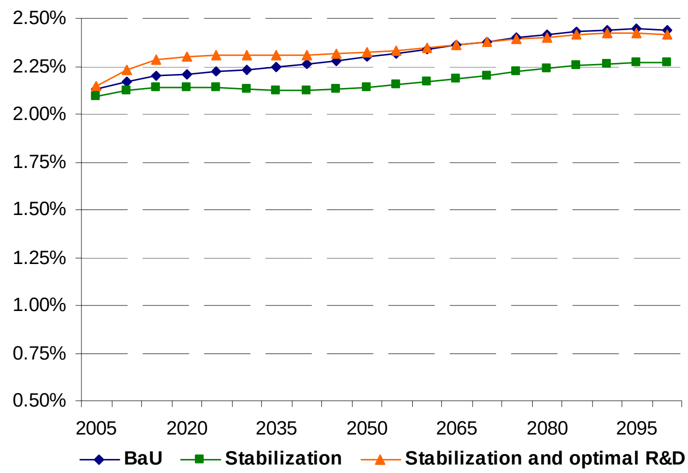

Figure 3. Investments in non-energy R&D/GWP.

6. Addressing the knowledge externality: R&D policies

In this section we study the implication of addressing only the knowledge externality by means of R&D policies that reduce the gap between the private and the social return to knowledge creation. R&D policies typically increase the attractiveness of knowledge creation by reducing the cost of innovation by means of subsidies or by increasing the reward to innovators with the imposition of constraints to knowledge circulation. In this case, we are not interested in the specificities of R&D policy, nor in its cost. In this section our aim is to assess the implications for the environmental externality of a hypothetical R&D policy that internalises all knowledge externalities in the energy sector first and then in both sectors. R&D policies that increase the rate of technical change are often proposed to solve both environmental and knowledge market failures. Here we provide a test of this proposition.

We consider two different R&D policies. First, only the externality of energy R&D is internalised (R&D Policy Energy). Second, externalities in both sectors are internalised (R&D Policy). Figure 4 and Figure 5 display the time path of the ratio of R&D when the policy is implemented and R&D in the BaU for the energy and non-energy sectors. We record a sharp increment of energy R&D spending when sectoral spillovers are internalised(i.e. when the social planner acknowledges the contribution of energy knowledge to the production of non-energy knowledge). Disentangling the exact forces at work is difficult because of productivity feedbacks driven by the mutual link between the two innovation possibility frontiers and by the complementarity of the two knowledge stocks.[16] The R&D policy in the energy sector leads to higher energy R&D spending, which increases the productivity of non-energy knowledge creation (see the higher spending in non-energy R&D induced by the energy R&D policy in Figure 5) and then in a positive productivity feedback for energy R&D investments.

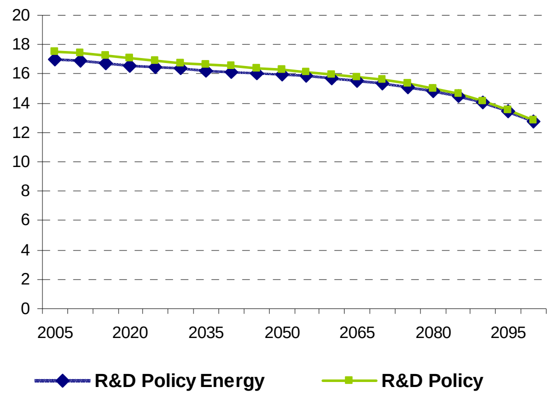

Figure 4. Ratio between investments in Energy R&D under different policy schemes and energy

[16] In this respect, to test the existence of complementarity across the two sectors we performed an exercise in which we measure the impact of a forced expansion of energy R&D investments on non-energy R&D investments in the absence of spillovers. Energy R&D investments are required to be, in each region, exactly equal to the optimal path determined when spillovers are fully internalised. We find that non-energy R&D investments, respond positively to an increase of energy R&D, revealing a degree of complementarity between the two knowledge stocks.

R&D investments in BaU.

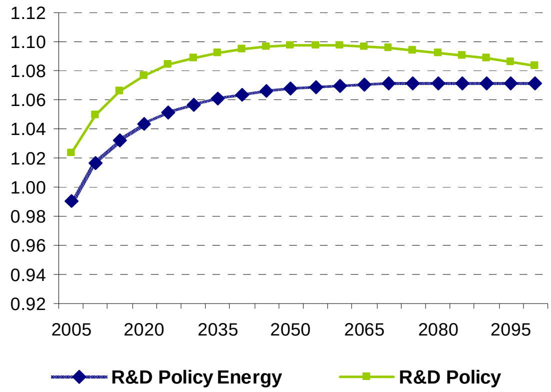

Figure 5. Ratio between investments in non-energy R&D under different policy schemes and non-energy R&D investments in BaU.

Both policies induce higher spending in R&D and an increment of both knowledge stocks with respect to the BaU. The increment of knowledge (i.e. of productivity) in the two sectors has opposite effects on energy demand: if from one side higher productivity of the energy input determines a lower demand of energy, from the other side the increased productivity of the non-energy input pushes for a higher demand of the complementary energy input. The final outcome on energy demand is driven by the relative strength of these effects, which is ultimately determined by the relative scarcity of the energy and non-energy inputs. In our BaU scenario, in the long run, technical change is directed towards energy-biased knowledge because energy is relatively more abundant than the capital-labour input. In both R&D Policy scenarios this effect is enhanced and technical progress in the long run becomes more and more energy-biased; thus, the demand of energy increases. The carbon intensity of energy remains largely unaffected because regions behave non-cooperatively on the global commons and do not internalise the environmental externality. Therefore, the R&D policies address the knowledge market failure without controlling for the environmental one. The implications of the two scenarios on CO_2 emissions are depicted in Figure 6.

Overall, R&D policies (including the one that internalises energy R&D externality) increase *voracity*, i.e. the attitude of countries in a non-cooperative setting to grab as much as possible of a common good, to preserve rate of return equalisation, thus exacerbating climate damage.

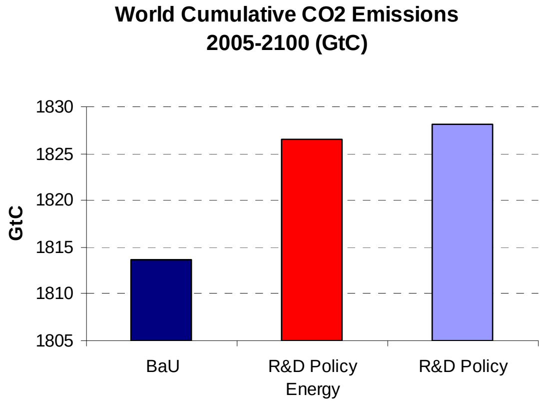

Figure 6. World cumulative CO_2 emissions (2005-2100).

7. Addressing both environmental and knowledge externalities: policy costs and welfare comparison

The previous sections have shown that addressing only the knowledge externalities increases the environmental problem and addressing only the environmental externality is, at best, not sufficient to bring R&D investments to the socially desirable level. In fact, the environmental policy exacerbates the knowledge externality in the non-energy sector. Therefore, at least in our modelling context, policies that address both externalities appear to be socially desirable.

A first approach to evaluate the attractiveness of different policy mixes is to check their impact on GWP. This is the most preferred method in climate policy analysis because it allows the aggregation of benefits and costs without the need of a social welfare function.[17] Figure 7 shows that the energy R&D policy has a remarkable impact on stabilisation costs: combining an energy R&D policy to the stabilisation policy would reduce costs to 0.14% of GDP for OECD countries and would also cut them considerably in non-OECD ones. At global level, stabilisation costs would be reduced to roughly one fourth of what they would be without the energy R&D policy. As expected, the energy R&D policy has a greater impact on costs in OCED countries, were the bulk of the knowledge externality is found. Figure 7 also shows that internalising all knowledge externalities reduces stabilisation costs further, even if by a lesser extent than the energy R&D policy. Stabilisation costs virtually disappear for OCED countries. For non-OECD countries the reduction of costs is less pronounced, as expected, and at global

[17] Stabilisation costs are measured as the discounted sum of year–by-year GWP differences between the policy scenarios and the BaU scenario. It is expressed as a percentage of the BaU scenario GWP. As mentioned before, we abstract here from the complex assessment of the costs of the R&D policy.

level internalising non-energy R&D externalities reduces stabilisation costs of 0.1% of discounted GWP.

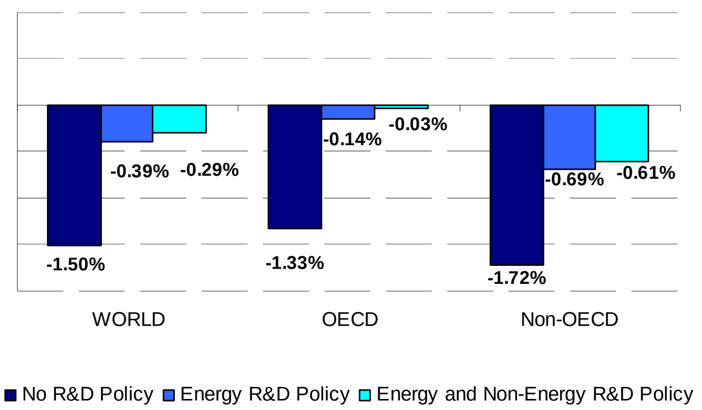

Figure 7. Discounted Stabilisation policy cost.

The fact that complementing the Stabilisation policy with an R&D policy brings a reduction of stabilisation costs is in line with the findings of Goulder and Schneider (1997) and Popp (2006). However, there are some important differences between the three models and the policies examined. Goulder and Schneider (1997) focus on *intra*sectoral spillovers and find that an R&D policy reduces stabilisation costs only if it addresses R&D externalities in all sectors. If restricted only to sectors with low emissions, the R&D policy increases stabilisation costs. Popp (2006) shows that higher spending in energy R&D reduces only marginally stabilisation costs because it crowds out non-energy R&D investments. The crowding-out is exogenous because Popp does not model the explicit knowledge accumulation in the non-energy sector. Contrary to Popp (2006) we do not impose exogenous crowding-out assumptions because we model both knowledge stocks. We find that a stabilisation policy together with an R&D policy targeted at the only energy sector is significantly less costly than the stabilisation policy alone. We find that energy R&D does not crowd-out non-energy R&D and, thanks to intersectoral spillovers, the policy induced increase in energy efficiency R&D *spills over* to the non-energy sector, contributing to knowledge accumulation and the reduction of knowledge externalities.

A more appropriate method to compare alternative policies is to rank them using regional welfare – i.e. the discounted sum of log utility of consumption per capita.[18] Table displays the

[18] A global analysis would require a global welfare function which is subject to complex evaluations of weighting schemes of regional welfares. The discount rate used is the pure rate of time preference. The regions of the WITCH model are: CAJANZ (Canada, Japan, New Zealand); USA; LACA (Latin America, Mexico and Caribbean); WEURO (Western Europe); EEURO (Estern Europe); MENA (Middle

relative regional preference ordering among the Stabilisation scenario, the Stabilisation R&D Policy Energy, in which only the energy sector externality is internalised, and the Stabilisation R&D Policy scenario, in which all knowledge externalities are internalised. Preferences are ranked in decreasing order and the policy mix with the highest welfare is ranked number one.

	OECD					non-OECD						
	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
Stabilization	3	3	3	3	3	3	3	3	3	3	3	3
Stabilization R&D Policy Energy	1	1	1	1	1	1	1	2	2	1	2	1
Stabilization R&D Policy	2	2	2	2	2	2	2	1	1	2	1	2

Table 3. Welfare ranking of different policy mixes.

Addressing knowledge externalities is welfare enhancing for all regions, and for most of them an R&D policy that targets externalities only for energy R&D is preferred to an R&D policy that internalises all knowledge externalities. This result is important because it shows that it is rational to pay special attention to energy R&D policies in a Stabilisation scenario. The idea that once the environmental externalities are corrected, all kinds of R&D should be treated the same is compelling, but it is valid only in a simplified setting, as in Nordhaus (2009). In our model we find a different result for two main reasons. First, an R&D policy, which targets also the non-energy sector increases the productivity of non-energy inputs and causes a higher demand of energy – because technical change is energy biased. Second, the equilibrium of the WITCH model is the result of an open-loop Nash game in which countries do not coordinate their actions to achieve an optimum at planetary scale. Therefore, regions do not coordinate themselves when they implement the R&D policy and look only at the national optimal level of R&D spending. As a result, they increase the demand of energy beyond the globally optimal level and the price of emissions permits rises: in our Stabilisation R&D Policy scenario the carbon price is roughly 1% higher over the whole century than in the Stabilisation R&D Policy Energy scenario. Countries with relatively higher carbon intensity suffer higher stabilisation costs and see their welfare reduced, while Sub-Saharan Africa (SSA), South Asia (SASIA) and East Asia (EASIA), all net sellers of emissions allowances, gain from both a higher productivity of the economy and a higher carbon price. This explains the results shown in Table.

East and North Africa); SSA (Sub-Saharan Africa excl. South Africa); TE (Transition Economies); SASIA (South Asia); CHINA (including Taiwan); EASIA (South East Asia); KOSAU (Korea, South Africa, Australia).

A final insight that we can draw from this enhanced version of the WITCH model with directed technical change, is how estimates of stabilisation costs change if the constraints on emissions is imposed on an economy in which investments in R&D are equal to the socially optimal level. We find that the cost of the stabilisation policy is higher if the starting point is an economy in which all knowledge externalities are internalised. In particular, not only stabilisation costs increase in absolute value, as it is reasonable to expect in economies that are more efficient and thus have higher output, but they are also higher in percentage terms as Figure 8 shows. The reason is the non-linearity of marginal abatement costs: an economy that has no constraints on emissions but starts with higher R&D investments and thus higher output, will have higher emissions, and therefore higher marginal abatement costs.

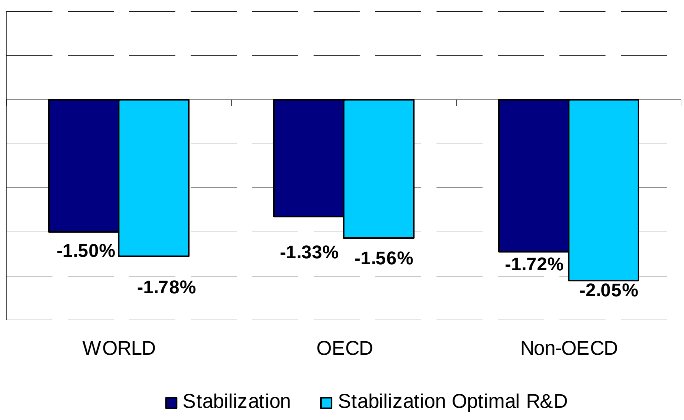

Figure 8 Discounted Stabilisation Policy Cost in second-best or optimal world.

8. Sensitivity analysis

In this section we present results of a sensitivity analysis on the elasticity of new knowledge creation with respect to intersectoral spillovers, to check the robustness of the main findings of our work. The value of the elasticity has been varied in a reasonable range around the central value 0.135 .

The first result to test is the impact of the stabilisation policy on non-energy knowledge accumulation. We find that the ratio of non-energy R&D investment in the Stabilisation scenario to non-energy R&D investment in the BaU scenario is only minimally affected by different assumptions on the elasticity of substitution (see Figure 9, where the central case is depicted by a solid line).

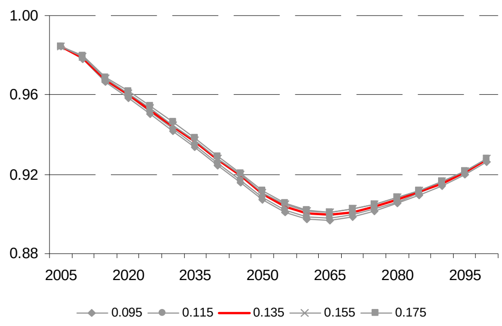

Figure 9. Ratio of non-energy R&D in the Stabilization Scenario to non-energy R&D in the BaU.

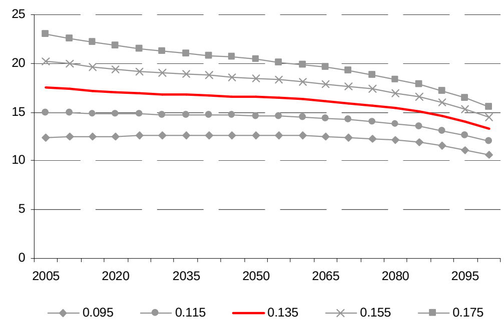

Figure 10. Ratio between investments in energy R&D with the R&D policy and energy R&D investments in BaU

The second result that we test is the sharp increment of energy R&D investments when the R&D policy is implemented. We can confirm that the R&D policy substantially increases the optimal amount of energy R&D investments under a sufficiently large range of elasticity parameters, as shown in Figure 10. The increment of spending in energy R&D caused by the R&D policy remains remarkable, even for values of the elasticity of substitution that are at the lower bound of empirical estimates.

We then consider the effect of implementing both climate and knowledge policies. As shown in Figure 11 and in Figure 12 the higher the value of elasticity, the greater the impact is of internalising knowledge externalities on both total R&D and on the costs of stabilisation. We even find that for value of the elasticity greater than 0.135, GWP increases with respect to the BaU when knowledge externalities are internalised.

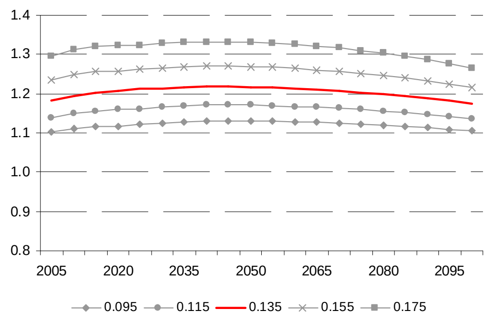

Figure 11 Ratio of R&D investments with stabilisation and R&D policy to R&D investments with stabilisation.

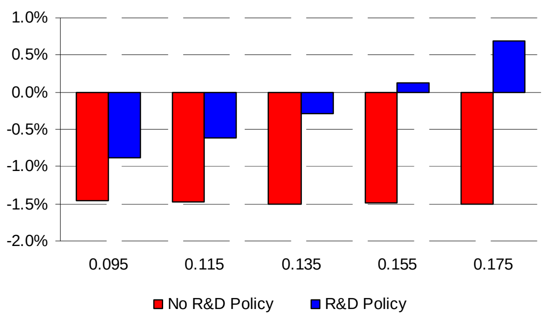

Figure 12 Discounted stabilisation policy costs, with and without R&D policy.

Finally we test the impact on emissions by internalising only knowledge externalities. As shown in Figure 13 we find a positive correlation between emissions and the value of elasticity. We also find that for all values of elasticities included in our analysis, implementing only one policy to correct market failure in knowledge sector always increases emissions.

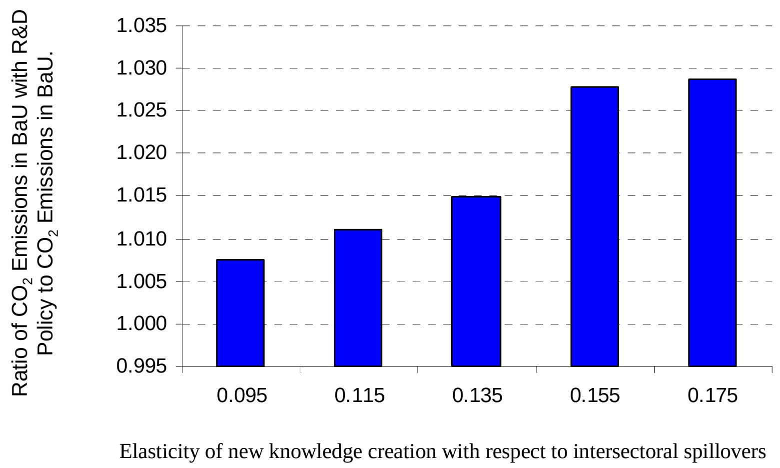

Figure 13. Ratio of CO_2 emissions in BaU with R&D policy to CO_2 emissions in BaU.

9. Conclusions

This paper contributes to the literature by expanding our understanding of the optimal mix of climate policies. In particular, the aim of this paper is to answer three policy questions that are relevant for the design of climate policy. First, what is the optimal response, in terms of investments in R&D of a policy to stabilise the atmospheric concentration of GHGs in a second-best framework? Second, what would be the optimal amount of R&D spending in the energy and non-energy sectors and what would be the environmental consequences of addressing only the knowledge externality? Third, what are the welfare implications of a policy mix that combines a stabilisation policy with R&D policies to support the optimal level of innovation?

We answer the above questions using an enhanced version of the WITCH model with directed technical change in which we have explicitly modelled intersectoral spillovers. R&D investments can be used to increase the productivity of the energy input and of non-energy inputs. Knowledge spills from one sector to the other, contributing to the generation of new ideas in a sector in which it was not originally accumulated.

We find that climate policy internalises only partially knowledge externalities in the energy sector and it even worsens market failures in the non-energy sector. This result confirms what was already found by Carraro, Massetti and Nicita (2009) in a model without intersectoral spillovers. Correcting the environmental externality alone has contrasting effects on the knowledge externality. Given the relative size of the two sectors, the stabilisation policy induces a lower amount of R&D spending than in the BaU. The answer to the first question is that the stabilisation policy brings us farther from the optimal level of R&D spending. The stabilisation policy thus increases the need for policies to correct for the knowledge externality instead of reducing it.

When only the knowledge externalities are corrected, we find that *voracity* – i.e. the attitude of countries to grab as much as possible of a common resource in a non-cooperative setting – exacerbates the environmental externality. Higher productivity, without a specific control for environmental externalities, is automatically translated into higher energy demand. Without any incentive to decarbonise energy, this results in higher carbon emissions and increased global warming. Interestingly, this happens also when we correct externalities only in the energy sector, enhancing the overall energy efficiency of the economies.

It seems that correcting both externalities is welfare enhancing with respect to enacting the single policies alone. The question is, however, what is the optimal mix of these policies? If we use GDP to compare the policy mixes, we find lower stabilisation costs if we complement the environmental policy with an R&D policy that internalise both knowledge externalities. If instead, we compare the policy scenarios using discounted utility, which is a more appropriate indicator of welfare than GDP, we obtain an important result: the preferred policy mix (in most regions) combines the Stabilisation policy with a policy to correct knowledge market externalities in the energy R&D sector alone. We thus find evidence to support the idea to combine a stabilisation policy with a policy to support energy R&D only.

So far, the debate on the optimal policy mix has been intense but vague. With this paper we have introduced a more sophisticated approach to describe knowledge dynamics by providing insights to the modelling community. We have also produced a first set of results that give substance to policy discussions.

References

Bosetti V, Carraro C, Massetti E, Tavoni M (2008) International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Economics 30:2912-2929.

Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M (2006) WITCH: A world induced technical change hybrid model. The Energy Journal, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

Bosetti V, Carraro C, Duval R, Sgobbi A, Tavoni M (2009a) The role of R&D and technology diffusion in climate change mitigation: New Perspectives using the WITCH Model. OECD Economics Department Working Paper No. 664, February 2009.

Bosetti V, De Cian E, Sgobbi A, Tavoni M (2009b) The 2008 WITCH Model: New Model Features and Baseline. FEEM Nota di Lavoro No 95.09.

Bosetti, V., E. Massetti, M. Tavoni (2007) The WITCH model: structure, baseline, solutions. FEEM Nota di Lavoro No 10.07.

Carraro C, Massetti E, Nicita L (2009) How does climate policy affect technical change? An analysis of the direction and pace of technical progress in a climate-economy model. The Energy Journal, Special Issue on Climate Change Policies After 2012, October 2009 30: 7-38.

Chang K (1994) Capital-energy substitution and the multi-level CES production function. Energy Economics 16(1):22–26.

Gillingham K, Newell RG, Pizer WA (2008) Modeling endogenous technological change for climate policy analysis. Energy Economics 30(6):2734-2753.

Goulder LH, Schneider SH (1999) Induced technological change and the attractiveness of CO_2 abatement policies. Resource and Energy Economics 21:211-253.

Griliches Z (1957) Hybrid corn: an exploration in the economics of technological change. Econometrica 25(4):501-522.

Griliches Z (1992) The search for R&D spillovers. Scandinavian Journal of Economics 94:29-47.

Grossman GM, Helpman E (1991). Innovation and growth in the global economy. Cambridge, Mass.: MIT Press.

Hall, B. (1996) The private and social returns to research and development, in Smith, B. and Barfield, C. (eds.), Technology, R&D, and the Economy, Brookings, Washington, D.C., pp. 140–183.

Jaffe, A.B. (1986) Technological opportunity and spillover of R&D: Evidence from firms' patents, profits, and market value. American Economic Review , 76: 984–1001.

Jaffe, A. B., Newell, R.G., Stavins R. N. (2005) A Tale of Two Market Failures: Technology and Environmental policy. Ecological Economics, 54: 164-174.

Jones CI (1999) Growth: with or without scale effects? American Economic Review 89(2):139-144.

Jones CI, Williams JC (1998) Measuring the social return to R&D. The Quarterly Journal of Economics 113(4):1119-1135.

Keller W (2002) Trade and the transmission of technology. Journal of Economic Growth 7:5-24.

Keller W (2004) International technology diffusion. Journal of Economic Literature 42(3):752-782.

Li CW (2000) Endogenous vs. semi-endogenous growth in a two-R&D-sector model. The Economic Journal 110(14):109-122.

Malerba F, Mancusi ML, Montobbio F (2007) Innovation, international R&D spillovers and the sectoral heterogeneity of knowledge flows. CESPRI working paper no 204.

Mansfield, E. (1977) Social and private rates of return from industrial innovations. Quarterly Journal of Economics 91: 221–240.

Mansfield, E. (1996) Microeconomic policy and technological change, in Fuhrer, J.C. and Little, J.S. (eds.), Technology and Growth: Conference Proceedings, Federal Reserve Bank of Boston, pp. 183–200.

Nordhaus WD (1990) Economic approaches to greenhouse warming. In Global Warming: Economi Policy Approaches, eds. RD Dornbush and JM Poterba:33-68. Cambridge, MA: MIT Press, 1990.

Nordhaus WD (2002) Modeling induced innovation in climate change policy. In Grubler A, Nakicenovic N, Nordhaus WD, Modeling induced innovation in climate change policy, Resources for the Future Press, Washington, 2002.

Nordhaus WD (2009) Designing a friendly space for technological change to slow global warming. Paper presented at the Snowmass Conference on Technologies to Combat Global Warming, Snowmass (CO), August 3-4, 2009.

Popp D (2004) ENTICE: endogenous technological change in the DICE model of global warming. Journal of Environmental Economics and Management 48:742-768.

Popp D (2006) R&D subsidies and climate policy: Is there a "free lunch"?” Climatic Change, 77: 311-341.

Popp D, Newell RG (2009) Where does energy R&D come from? Examining crowding out from environmentally-friendly R&D. NBER Working Paper No. 15423, Oct 2009.

Romer PM (1990) Endogenous technical change. Journal of Political Economy 98:71-102.

Schneider S, Goulder L (1997) Achieving low-cost emissions targets. Nature 389:13–14.

Van der Werf E (2007) Production functions for climate policy modeling: an empirical analysis. FEEM Nota di Lavoro No 47.07 .

Wieser R (2005) Research and development productivity and spillovers: empirical evidence at the firm level. Journal of Economic Surveys 19(4):587-621.

Appendix. Model Equations and List of Variables.

In this Appendix we reproduce the main equations of the model. For a full description of the model please refer to Bosetti, Massetti and Tavoni (2007). The list of variables is reported at the end. In each region, indexed by *n*, a social planner maximises the following utility function:

$$W(n) = \sum_t U\left[C(n,t), L(n,t)\right]R(t) = \sum_t L(n,t)\left\{\log\left[c(n,t)\right]\right\}R(t)\,, \qquad \text{(A1)}$$

where *t* are 5-year time spans and the pure time preference discount factor is given by:

$$R(t) = \prod_{v=0}^{t}\left[1+\rho(v)\right]^{-5}\,, \qquad \text{(A2)}$$

where the pure rate of time preference $\rho(v)$ is assumed to decline over time. Moreover, $c(n,t) = \frac{C(n,t)}{L(n,t)}$ is per capita consumption.

<u>*Economic module*</u>

The budget constraint defines consumption as net output less investments:

$$\begin{aligned} C(n,t) = {} & Y(n,t) - I_C(n,t) - I_{R\&D,EN}(n,t) - I_{R\&D,KL}(n,t) \\ & -\sum_j I_{R\&D,j}(n,t) - \sum_j I_j(n,t) - \sum_j O\&M_j(n,t) \end{aligned} \qquad \text{(A3)}$$

Where *j* denotes energy technologies.

Output is produced via a nested CES function that combines a capital-labour aggregate and energy; capital and labour are obtained from a CES function. The climate damage Ω reduces gross output; to obtain net output we subtract the costs of the fuels *f* and of CCS:

$$\begin{aligned} Y(n,t) = {} & \frac{TFP(n,t)\left[\alpha_Y(n)\cdot KLS^{\rho_Y} + (1-\alpha_Y(n))\cdot ES(n,t)^{\rho_Y}\right]^{1/\rho_Y}}{\Omega(n,t)} \\ & -\sum_f \left(P_f(n,t)X_{f,extr}(n,t) + P_f^{\text{int}}(t)X_{f,netimp}(n,t)\right) \\ & -P_{CCS}(n,t)CCS(n,t) \end{aligned} \qquad . \qquad \text{(A4)}$$

Total factor productivity $TFP(n,t)$ evolves exogenously with time.

Energy services are an aggregate of energy and a stock of knowledge combined with a CES function:

$$ES(n,t) = \left[\alpha_{HE}(n)HE(n,t)^{\rho_{ES}} + \alpha_{EN}(n)EN(n,t)^{\rho_{ES}}\right]^{1/\rho_{EN}}\,. \qquad \text{(A5)}$$

Energy is a combination of electric and non-electric energy:

$$EN(n,t) = \left[\alpha_{EL}EL(n,t)^{\rho_{EN}} + \alpha_{NEL}NEL(n,t)^{\rho_{EN}}\right]^{1/\rho_{EN}}\,. \qquad \text{(A6)}$$

Each factor is further decomposed into several sub-components. Figure 2 portrays a graphical illustration of the energy sector. Factors are aggregated using CES, linear and Leontief production functions.

Capital-labour services are obtained aggregating a capital-labour input and a knowledge stock with a CES function:

$$KLS(n,t) = \left[\alpha_{HKL}(n)HKL(n,t)^{\rho_{KLS}} + \alpha_{KL}(n)KL(n,t)^{\rho_{KLS}}\right]^{1/\rho_{KL}} \qquad \text{(A7)}$$

The capital-labour input is a CES combination of capital and labour. Labour is assumed to be equal to population and evolves exogenously.

$$KL(n,t) = \left[\alpha_K(n)K_C(n,t)^{\rho_{KL}} + \alpha_L(n)L(n,t)^{\rho_{KL}}\right]^{1/\rho_{KL}} \qquad \text{(A8)}$$

Final good capital accumulates following the standard perpetual rule:

$$K_C(n,t+1) = K_C(n,t)(1-\delta_C) + I_C(n,t). \quad \text{(A9)}$$

New ideas which contribute to the stock of energy knowledge, $Z_{HE}(n,t)$, are produced using R&D investments, $I_{R\&D,EN}(n,t)$, together with the previously cumulated knowledge stock $HE(n,t)$:

$$Z_{HE}(n,t) = a\, I_{HE}(n,t)^b\, HE(n,t)^c\, HKL(n,t)^d \cdot \quad \text{(A10)}$$

Similarly, new ideas in the non-energy sector are generated as follows:

$$Z_{HKL}(n,t) = f\, I_{HKL}(n,t)^g\, HKL(n,t)^h\, HE(n,t)^i \quad \text{(A11)}$$

The two knowledge stocks evolve as follows:

$$HE(n,t+1) = HE(n,t)(1-\delta) + Z_{HE}(n,t) \quad \text{(A12)}$$

$$HKL(n,t+1) = HKL(n,t)(1-\delta) + Z_{HKL}(n,t) \quad \text{(A13)}$$

For illustrative purposes, we show how electricity is produced via capital, operation and maintenance and resource use through a zero-elasticity Leontief aggregate:

$$EL_j(n,t) = \min\{\mu_{n,j} K_j(n,t); \tau_{n,j} O\&M_j(n,t); \varsigma_j X_{j,EL}(n,t)\}. \quad \text{(A14)}$$

Capital for electricity generation technologies accumulates as follows:

$$K_j(n,t+1) = K_j(n,t)(1-\delta_j) + \frac{I_j(n,t)}{SC_j(n,t)}, \quad \text{(A15)}$$

where, for selected technologies, the new capital investment cost *SC(n,t)* decreases with the world cumulated installed capacity by means of Learning-by-Doing:

$$SC_j(n,t) = B_j(n) \sum_t \sum_n K_j(n,t)^{-\log_2 PR_j}. \quad \text{(A16)}$$

Operation and maintenance is treated as an investment that fully depreciates every year. The resources employed in electricity production are subtracted from output in equation A3 and A4. Their prices are calculated endogenously using a reduced-form cost function that allows for non-linearity in both the depletion effect and in the rate of extraction:

$$P_f(n,t) = \chi_f(n) + \pi_f(n)\left[Q_f(n,t-1)/\overline{Q}_f(n,t)\right]^{\psi_f(n)} \quad \text{(A17)}$$

where Q_f is cumulative extraction of fuel f:

$$Q_f(n,t-1) = Q_f(n,0) + \sum_{s=0}^{t-1} X_{f,extr}(n,s). \quad \text{(A18)}$$

Each country covers consumption of fuel f, $X_f(n,t)$, by either domestic extraction or imports, $X_{f,netimp}(n,t)$, or by a combination of both. If the country is a net exporter, $X_{f,netimp}(n,t)$ is negative.

$$X_f(n,t) = X_{f,extr}(n,t) + X_{f,netimp}(n,t) \quad \text{(A19)}$$

<u>Climate Module</u>

GHGs emissions from combustion of fossil fuels are derived by applying stoichiometric coefficients to the total amount of fossil fuels utilised minus the amount of CO_2 sequestered:

$$CO_2(n,t) = \sum_f \omega_{f,CO_2} X_f(n,t) - CCS(n,t). \quad \text{(A20)}$$

When a cap on emission (CAP) is included we have an additional equation, constraining emissions, given the possibility to sell and buy permits:

$$CO_2(n,t) = CAP(n,t) + NIP(n,t) \quad \text{(A21)}$$

In addition, carbon permits revenues/expenses enter the budget constraint:

$$\begin{aligned} C(n,t) = {} & Y(n,t) - I_C(n,t) - I_{R\&D,EN}(n,t) - I_{R\&D,KL}(n,t) \\ & - \sum_j I_{R\&D,j}(n,t) - \sum_j I_j(n,t) - \sum_j O\&M_j(n,t) - p(t)NIP(n,t) \end{aligned} \quad \text{(A3')}$$

The damage function impacting output varies with global temperature:

$$\Omega(n,t) = \frac{1}{1+\left(\theta_{1,n}T(t)+\theta_{2,n}T(t)^2\right)} \cdot \tag{A22}$$

Temperature increases through augmented radiating forcing *F(t)*:

$$T(t+1) = T(t) + \sigma_1\left\{F(t+1) - \lambda T(t) - \sigma_2\left[T(t) - T_{LO}(t)\right]\right\} \tag{A23}$$

which in turn depends on CO_2 concentrations:

$$F(t) = \eta\left\{\log\left[M_{AT}(t)/M_{AT}^{PI}\right] - \log(2)\right\} + O(t)\ , \tag{A24}$$

caused by emissions from fuel combustion and land use change:

$$M_{AT}(t+1) = \sum_n \left[CO_2(n,t) + LU_j(t)\right] + \phi_{11}M_{AT}(t) + \phi_{21}M_{UP}(t)\ , \tag{A25}$$

$$M_{UP}(t+1) = \phi_{22}M_{UP}(t) + \phi_{12}M_{AT}(t) + \phi_{32}M_{LO}(t)\ , \tag{A26}$$

$$M_{LO}(t+1) = \phi_{33}M_{LO}(t) + \phi_{23}M_{UP}(t)\ . \tag{A27}$$

CESifo Working Paper Series

for full list see www.cesifo-group.org/wp
(address: Poschingerstr. 5, 81679 Munich, Germany, office@cesifo.de)

2925 Erkki Koskela and Jan König, Profit Sharing, Wage Formation and Flexible Outsourcing under Labor Market Imperfection, January 2010

2926 Gabriella Legrenzi and Costas Milas, Spend-and-Tax Adjustments and the Sustainability of the Government's Intertemporal Budget Constraint, January 2010

2927 Piero Gottardi, Jean Marc Tallon and Paolo Ghirardato, Flexible Contracts, January 2010

2928 Gebhard Kirchgässner and Jürgen Wolters, The Role of Monetary Aggregates in the Policy Analysis of the Swiss National Bank, January 2010

2929 J. Trent Alexander, Michael Davern and Betsey Stevenson, Inaccurate Age and Sex Data in the Census PUMS Files: Evidence and Implications, January 2010

2930 Stefan Krasa and Mattias K. Polborn, Competition between Specialized Candidates, January 2010

2931 Yin-Wong Cheung and Xingwang Qian, Capital Flight: China's Experience, January 2010

2932 Thomas Hemmelgarn and Gaetan Nicodeme, The 2008 Financial Crisis and Taxation Policy, January 2010

2933 Marco Faravelli, Oliver Kirchkamp and Helmut Rainer, Social Welfare versus Inequality Concerns in an Incomplete Contract Experiment, January 2010

2934 Mohamed El Hedi Arouri and Christophe Rault, Oil Prices and Stock Markets: What Drives what in the Gulf Corporation Council Countries?, January 2010

2935 Wolfgang Lechthaler, Christian Merkl and Dennis J. Snower, Monetary Persistence and the Labor Market: A New Perspective, January 2010

2936 Klaus Abberger and Wolfgang Nierhaus, Markov-Switching and the Ifo Business Climate: The Ifo Business Cycle Traffic Lights, January 2010

2937 Mark Armstrong and Steffen Huck, Behavioral Economics as Applied to Firms: A Primer, February 2010

2938 Guglielmo Maria Caporale and Alessandro Girardi, Price Formation on the EuroMTS Platform, February 2010

2939 Hans Gersbach, Democratic Provision of Divisible Public Goods, February 2010

2940 Adam Isen and Betsey Stevenson, Women's Education and Family Behavior: Trends in Marriage, Divorce and Fertility, February 2010

2941 Peter Debaere, Holger Görg and Horst Raff, Greasing the Wheels of International Commerce: How Services Facilitate Firms' International Sourcing, February 2010

2942 Emanuele Forlani, Competition in the Service Sector and the Performances of Manufacturing Firms: Does Liberalization Matter?, February 2010

2943 James M. Malcomson, Do Managers with Limited Liability Take More Risky Decisions? An Information Acquisition Model, February 2010

2944 Florian Englmaier and Steve Leider, Gift Exchange in the Lab – It is not (only) how much you give …, February 2010

2945 Andrea Bassanini and Giorgio Brunello, Barriers to Entry, Deregulation and Workplace Training: A Theoretical Model with Evidence from Europe, February 2010

2946 Jan-Emmanuel De Neve, James H. Fowler and Bruno S. Frey, Genes, Economics, and Happiness, February 2010

2947 Camille Cornand and Frank Heinemann, Measuring Agents' Reaction to Private and Public Information in Games with Strategic Complementarities, February 2010

2948 Roel Beetsma and Massimo Giuliodori, Discretionary Fiscal Policy: Review and Estimates for the EU, February 2010

2949 Agnieszka Markiewicz, Monetary Policy, Model Uncertainty and Exchange Rate Volatility, February 2010

2950 Hans Dewachter and Leonardo Iania, An Extended Macro-Finance Model with Financial Factors, February 2010

2951 Helmuth Cremer, Philippe De Donder and Pierre Pestieau, Education and Social Mobility, February 2010

2952 Zuzana Brixiová and Balázs Égert, Modeling Institutions, Start-Ups and Productivity during Transition, February 2010

2953 Roland Strausz, The Political Economy of Regulatory Risk, February 2010

2954 Sanjay Jain, Sumon Majumdar and Sharun W. Mukand, Workers without Borders? Culture, Migration and the Political Limits to Globalization, February 2010

2955 Andreas Irmen, Steady-State Growth and the Elasticity of Substitution, February 2010

2956 Bengt-Arne Wickström, The Optimal Babel – An Economic Framework for the Analysis of Dynamic Language Rights, February 2010

2957 Stefan Bauernschuster and Helmut Rainer, From Politics to the Family: How Sex-Role Attitudes Keep on Diverging in Reunified Germany, February 2010

2958 Patricia Funk and Christina Gathmann, How do Electoral Systems Affect Fiscal Policy? Evidence from State and Local Governments, 1890 to 2005, February 2010

2959 Betsey Stevenson, Beyond the Classroom: Using Title IX to Measure the Return to High School Sports, February 2010

2960 R. Quentin Grafton, Tom Kompas and Ngo Van Long, Biofuels Subsidies and the Green Paradox, February 2010

2961 Oliver Falck, Stephan Heblich, Alfred Lameli and Jens Suedekum, Dialects, Cultural Identity, and Economic Exchange, February 2010

2962 Bård Harstad, The Dynamics of Climate Agreements, February 2010

2963 Frederick van der Ploeg and Cees Withagen, Is There Really a Green Paradox?, February 2010

2964 Ingo Vogelsang, Incentive Regulation, Investments and Technological Change, February 2010

2965 Jan C. van Ours and Lenny Stoeldraijer, Age, Wage and Productivity, February 2010

2966 Michael Hoel, Climate Change and Carbon Tax Expectations, February 2010

2967 Tommaso Nannicini and Roberto Ricciuti, Autocratic Transitions and Growth, February 2010

2968 Sebastian Brauer and Frank Westermann, A Note on the Time Series Measure of Conservatism, February 2010

2969 Wolfram F. Richter, Efficient Education Policy – A Second-Order Elasticity Rule, February 2010

2970 Tomer Blumkin, Yoram Margalioth and Efraim Sadka, Taxing Children: The Re-distributive Role of Child Benefits – Revisited, February 2010

2971 Chang Woon Nam and Georg Wamser, Application of Regionally Varying Additionality Degrees in the Practice of EU Cohesion Policy, February 2010

2972 Ali Bayar, Frédéric Dramais, Cristina Mohora, Masudi Opese and Bram Smeets, Modeling Russia for Climate Change Issues, February 2010

2973 Magnus Söderberg, Informal Benchmarks as a Source of Regulatory Threat in Unregulated Utility Sectors, March 2010

2974 Piotr Wdowiński and Marta Malecka, Asymmetry in Volatility: A Comparison of Developed and Transition Stock Markets, March 2010

2975 Frans van Winden, Michal Krawczyk and Astrid Hopfensitz, Investment, Resolution of Risk, and the Role of Affect, March 2010

2976 Hyun-Ju Koh and Nadine Riedel, Do Governments Tax Agglomeration Rents?, March 2010

2977 Johann K. Brunner and Susanne Pech, Optimum Taxation of Bequests in a Model with Initial Wealth, March 2010

2978 Guglielmo Maria Caporale and Nicola Spagnolo, Stock Market Integration between three CEECs, Russia and the UK, March 2010

2979 Florian Englmaier, Ales Filipi and Ravi Singh, Incentives, Reputation and the Allocation of Authority, March 2010

2980 Konstantinos Angelopoulos, George Economides and Apostolis Philippopoulos, What is the Best Environmental Policy? Taxes, Permits and Rules under Economic and Environmental Uncertainty, March 2010

2981 Frederick van der Ploeg, Rapacious Resource Depletion, Excessive Investment and Insecure Property Rights, March 2010

2982 Wolfram F. Richter and Christoph Braun, Efficient Subsidization of Human Capital Accumulation with Overlapping Generations and Endogenous Growth, March 2010

2983 Francesco Cinnirella, Marc Piopiunik and Joachim Winter, Why Does Height Matter for Educational Attainment? Evidence from German Pre-Teen Children, March 2010

2984 Bernard Van Praag, Well-being Inequality and Reference Groups – An Agenda for New Research, March 2010

2985 Francesca Barion, Raffaele Miniaci, Paolo M. Panteghini and Maria Laura Parisi, Profit Shifting by Debt Financing in Europe, March 2010

2986 Alexander Haupt and Magdalena Stadejek, The Choice of Environmental Policy Instruments: Energy Efficiency and Redistribution, March 2010

2987 John Komlos and Marek Brabec, The Trend of BMI Values among US Adults, March 2010

2988 Emanuele Massetti and Lea Nicita, The Optimal Climate Policy Portfolio when Knowledge Spills across Sectors, March 2010