Optimal R&D Investments and the Cost of GHG Stabilization when Knowledge Spills across Sectors[*]

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Abstract

The present work analyses the effect of a stabilization policy of GHG in the atmosphere on the advancements of the technological frontier of both energy and non-energy sector when the two are linked through mutual intersectoral spillovers. The analysis is performed using WITCH, a dynamic integrated regional model of the world economy. We include intersectoral knowledge spillovers in a version of the model in which R&D investments can be directed towards energy and non-energy inputs. We find that, when a climate policy is imposed, R&D is re-directed towards energy knowledge and total optimal R&D investment decreases, due to a more than proportional contraction of non-energy R&D. However, the reallocation of investment across the two R&D sectors is less dramatic than when spillovers are not modelled, and, as a result, stabilization costs are reduced.

Keywords: Technical Change, Climate, Development, Innovation, Investments

JEL classification: C72, H23, Q25, Q28, O31, O41, Q54

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1. Introduction

There is now a wide agreement on the fact that any stringent climate policy will call for a tremendous effort in technological innovation. Therefore, it is well comprehensible that 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 model for climate policy analysis has greatly improved. 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 still very rarely described.

Several studies have pointed out that the social rates of return on R&D expenditure is higher (four time according to Jones and Williams, 1998) than the corresponding private rates. This results from the well established empirical finding that the estimated elasticities of TFP to R&D capital are higher at aggregate level than at firm level, and, as emphasized for example by Griliches (1992), is an implicit indication of the presence of technological spillovers.

Spillovers are generally acknowledged as a fundamental aspect of technical change. The new growth theory following the seminal work of Romer (1990), has emphasized the importance of both international R&D knowledge spillovers (Grossman and Helpman, 1991, ch.11 and 12), and intrasectoral and intersectoral R&D knowledge spillovers (Jones, 1999; Li 2000) in explaining countries' productivity. Those contributions have stimulated the development of a number of studies that estimate the impact of R&D spillovers from other firms, sectors or countries.[2] Overall the available empirical evidence supports the idea that spillovers effect are relevant and positive, even if the variety of methodologies and techniques applied has produced a considerable variation in estimates of the size of R&D spillovers and of their significance across studies.

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 intertemporal spillovers (e.g. Bosetti *et al*, 2008 introduces international energy-related knowledge spillovers in the WITCH model).

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[2] 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 .

However, despite international spillovers allow a richer description of trans-boundary knowledge diffusion and enlarge the scope of international technological cooperation, empirical studies provide evidence that inter-sectoral spillovers are extremely significant as claimed by Wieser (2005) in his broad review of the literature.

In order to fill this gap, in the present work we pioneer the introduction of inter-sectoral spillovers in an Integrated Assessment model. 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).

Without spillovers, models unrealistically assume that advance of technological frontiers of different sectors are mutually independent. and omit to consider the interactions among different drivers of technical change.

The goal of the present work is to study the effect that modeling inter-sectoral knowledge spillovers has on the advances of the technological frontier and on the costs of climate policy.

The paper is organized as follows. Section 2 lays out the details of the model. Section 3 explains the calibration procedure. Section 4 describes some basic features of the BaU and introduces some historical evidence on R&D patterns. Section 5 introduces and discusses the Stabilization Policy scenario. Conclusions follow.

2. Model Description

2.1 Short model description

WITCH -World Induced Technical Change Hybrid model- is a regional integrated assessment model designed to provide normative information on the optimal responses of world economies to climate damages and to model the effects of climate policy into the world economic systems. It is an hybrid model because it combines features of both top-down and bottom-up modeling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been expanded to yield a bottom-up like description of the energy sector. World countries are grouped in 12 regions whose strategic interactions are modeled using a game-theoretic approach. A climate module and a damage function provide the feedback on the economy of carbon dioxide emissions into the atmosphere.

WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments that have an impact on the level of mitigation – R&D effort, investment in energy technologies, fossil fuel expenditures. The regional specification of the model and the presence of strategic interaction among regions – through CO_2, exhaustible natural resources, technological spillovers – allows us to account for the incentives to free-ride. Also, investment strategies are optimized by taking into account both economic and environmental externalities. In WITCH, the energy sector is described with a sufficient degree of detail and permits a reasonable characterization of future energy and technological scenarios as well as an assessment of their compatibility with the goal of stabilizing greenhouse gases concentrations. Also, by endogenously modeling fuel (oil, coal, natural gas, uranium) prices, and the cost of storing the captured CO_2, the model can be used to evaluate the main impacts of mitigation policies on the energy system, in all its components. In the following section, we selectively present some features and equations of the model that are functional to our analysis of technological change. For a throughout description of the model see Bosetti *et al* (2006) and for calibration details and a discussion of the baseline see Bosetti, Massetti and Tavoni (2007).

2.2 Directed Technical Change with Intersectoral Spillovers

Gross output, $GY\left(n,t\right)$,[3] in country n at time t is produced by combining energy services, $ES\left(n,t\right)$, and capital-labor services $KLS\left(n,t\right)$ in a CES nest:[4]

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

Energy services and capital-labor services are obtained by aggregating raw inputs to knowledge, which raises their productivity. We use, as a proxy of knowledge, the cumulated stocks of R&D in the Non-Energy and Energy sectors, $HKL\left(n,t\right)$ and $HE\left(n,t\right)$, respectively. The aggregation between raw inputs and knowledge is assumed to follow a standard CES function:

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

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

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[3] Net output, $Y\left(n,t\right)$, 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 detail in the Appendix.

[4] Where $\rho = (\sigma - 1)/\sigma$ and σ is the elasticity of substitution.

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

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

This formulation is supported by empirical evidence, as carefully explained in Carraro, Massetti and Nicita (2009).[5]

As in previous versions of WITCH, the hybrid nature of the model allows us to portray endogenous technological change also from a bottom-up perspective, by letting Learning-by-Doing to reduce the cost of power generation plants.

2.3 The R&D Sectors

The production of new ideas that accumulates in the region's knowledge stocks follows an innovation possibility frontier specification. We account for two different types of knowledge spillovers. First, knowledge is produced 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). Second, with this study we introduce intersectoral knowledge spillovers by including among the inputs of the idea generating process in one sector 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:

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

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

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[5] See, among others: van der Werf (2007), Kemfert (1998) and Chang (1994).

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:

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

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

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, optimally derived in each country/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 internalizes knowledge externalities and chooses the optimal path of R&D investments accordingly. Our baseline scenario is constructed with the hypothesis that knowledge spills across sectors as an externality. With this set-up we reproduce the sub-optimal investment rate in knowledge as observed in reality.

3. Calibration

With respect to the standard version of the model[6] we adopt the same nesting structure of the production function as in Carraro, Massetti and Nicita (2009) to which we refer for a detailed description of empirical evidence supporting the chosen structure and value of parameters. The elasticity between energy and capital-labor services, σ_Y, is set equal to 0.5. The elasticity of substitution between labor and capital, σ_{KL}, is equal to 0.8 for all regions but China and South Asia, for which we allow for a greater elasticity of substitution (σ_{KL} equal to 0.85). We calibrate energy R&D as in Popp (2004). Parameters of the CES function between energy and knowledge and of the innovation possibility frontier are chosen to be consistent with historical levels and to reproduce the elasticity of Energy R&D to energy prices. The elasticity of

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[6] We use here the latest version of the model, WITCH08. In the latest version, the model has been updated with more recent 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.

substitution between energy and energy knowledge, σ_{ES}, is accordingly set equal to 1.67 and the same is assumed for the elasticity between capital-labor and non-energy knowledge, σ_{KLS}. R&D investments in the non-energy sector are also assumed to yield a return four times higher than the interest rate. The initial stock of Non-Energy knowledge is calibrated to obtain R&D investments in the initial time period which are about 2% of GDP, a figure very close to the historical one.

Finally, the value of the elasticity of new knowledge creation with respect to intersectoral spillovers is set equal to 0.16. Its calibration is based on both the contributions of Malerba et al. (2007) and Keller (2002). Malerba et al. (2007) estimate a spillover-augmented knowledge production function as the one we have assumed in our work. They find that, at macro level, the elasticity of knowledge creation with respect to intersectoral spillovers is between 0.11 and 0.20. Keller (2002) estimates the relative contribution to total productivity of intrasectoral, intersectoral and international spillovers. He finds that half of total productivity effect is due to own-sector R&D, about 30% comes from intersectoral domestic R&D, about 15% is due to intersectoral foreign R&D and only 5% comes from own-sector foreign R&D.

We calibrate the model with intersectoral knowledge spillovers in order to obtain the same knowledge stocks of Energy and Non-Energy R&D as in the model without spillovers. Given the chosen value for the elasticity of knowledge creation to intersectoral spillovers, we change parameters *c* and *h*, the exponents of knowledge stocks. By doing that we assume that the version of the model without spillovers already featured a well behaved time pattern for knowledge stocks. In fact, especially in the energy sector, the stock of knowledge has been calibrated to reproduce observed patterns of energy efficiency improvements. Since the stocks are identical with and without intersectoral spillovers, investments will be lower when spillovers are modelled. These extra resources are spread across the many different investment possibilities described in the model with very minor changes in the path of the other variables (see also Bosetti *et al*, 2008).

4. The Baseline Scenario

Our Baseline scenario 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 and experience technology spillovers in the electricity sector.[7]

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[7] In Bosetti *et al* (2008) and in other versions of the model there are also international knowledge spillovers in the Energy R&D sector. This previous version of the model does not model non-energy R&D investments.

Table 1 summarizes baseline trends of major variables and indicators of interest. GWP increases over the whole century, starting from 44 trillions in 2005 it increases to 365 trillions in 2105, an almost nine-fold expansion. Population grows at a declining rate and start decreasing at the end of the century. The gains in energy efficiency explain the reduction of emissions per unit of output, however, the strong expansion of output offsets all efficiency gains and overall carbon emissions increase throughout the century, leading to a doubling of CO_2 concentrations in the atmosphere.

The model yields a rather constant path of R&D expenditure, as share of GWP. As a result, the fraction of investment devoted to knowledge creation is increasing. The model also yields a slightly declining path of Energy R&D as share of GWP, a first increasing and then declining path of Non-Energy R&D as share of GWP, and a declining rate of Energy to Non-Energy R&D investments.

	2005	2025	2045	2065	2085	2105
GWP (Trillions, 2005 USD)	44	87	150	224	300	365
World Population (billions)	6.5	8.0	9.0	9.5	9.5	9.0
Carbon Intensity of Output	0.218	0.153	0.115	0.091	0.077	0.064
CO2 concentrations in the atmosphere (ppm)	390	444	516	599	689	775
R&D expenditure (%GWP)	1.682%	1.756%	1.760%	1.762%	1.744%	1.661%
Non-energy R&D (%GWP)	1.666%	1.742%	1.746%	1.748%	1.731%	1.648%
Energy R&D (%GWP)	0.016%	0.014%	0.014%	0.014%	0.013%	0.012%
Energy R&D (%Total Investment in R&D)	0.924%	0.818%	0.789%	0.775%	0.760%	0.742%

Table 1. Baseline Trend of Major Variables

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 GDP for OECD countries. Historic data show a slightly increasing trend over the past 25 years, starting from 1.9% in 1981 and reaching 2.25% in 2005. The same trend is predicted in the baseline scenario, with total R&D over GDP increasing from 2% in 2005 to almost 2.5% at the end of the century.

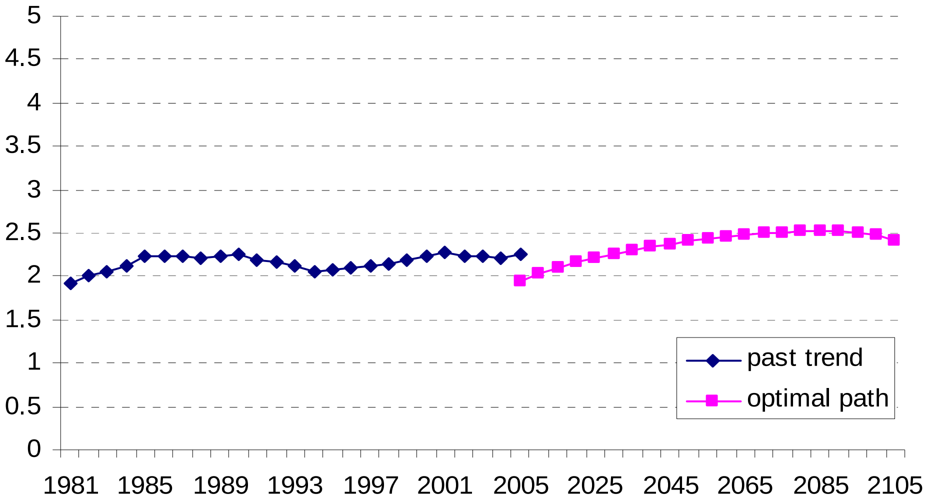

Figure 1. R&D as Percentage of GDP in OECD countries

5. Climate Policy: the Stabilization Scenario

The Stabilization Scenario is constructed 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 an "Equal per Capita" allocation of carbon allowances.

The path of emission we impose leads to a stabilization of CO_2 concentrations at 450ppm at the end of the century. This target is roughly equivalent to a 550ppm target with all Greenhouse Gases included.

	2005	2025	2045	2065	2085	2105
GWP (Trillions, 2005 USD)	44	86	147	218	295	367
World Population (billions)	6.5	8.0	9.0	9.5	9.5	9.0
Carbon Intensity of Output	0.218	0.113	0.047	0.022	0.015	0.012
CO2 concentrations in the atmosphere (ppm)	390	408	431	441	444	447
R&D expenditure (%GWP)	1.668%	1.705%	1.661%	1.649%	1.637%	1.570%
Non-energy R&D (%GWP)	1.649%	1.682%	1.632%	1.619%	1.610%	1.546%
Energy R&D (%GWP)	0.019%	0.023%	0.029%	0.030%	0.027%	0.023%
Energy R&D (%Total Investment in R&D)	1.136%	1.338%	1.763%	1.790%	1.635%	1.475%

Table 2. Stabilization Trends of Major Variables

Table 2 displays the optimal trend when the stabilization policy just briefly described is implemented. As expected, Gross World Product (GWP) over the whole optimization interval 2005-2105 is reduced. Discounted costs, measured as reductions of net GDPs and aggregated over regions, are -1.5% of baseline discounted GWP. Energy R&D shows an increasing trend while Non-Energy R&D investments are found to be lower than in the baseline scenario. The contraction of knowledge generation in the Non-Energy sector offsets increased knowledge creation in the Energy sector and, as a result, the model finds optimal to reduce total R&D investments and the pace of knowledge accumulation is slowed down.

This result matches that obtained and widely discussed in Carraro, Massetti and Nicita (2009). In the analysis performed in the previous contribution we showed that it is the mitigation policy, and not the increase in Energy R&D, that crowds out Non-Energy R&D investment. This happens because the implementation of the climate policy generates a contraction of the economy and because it slows down the pace of energy-biased technical change. In other words since our model features that higher R&D in the Non-Energy sector increases the demand of Energy; it is thus optimal to decrease technical progress in the Non-Energy sector when a stringent climate policy is imposed.

However, when we turn at comparing the magnitude of the change in Non-energy R&D and Energy R&D investment we discover that the model that includes inter-sectoral spillovers performs quite differently with respect to the model without spillovers as shown in figure 2 and figure 3.

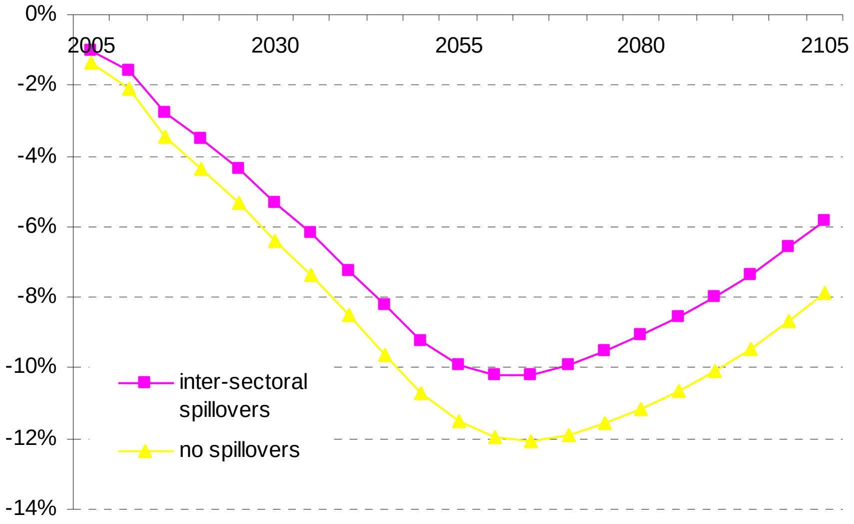

Figure 2. Percentage change of Investments in Non-Energy R&D: stabilization wrt bau

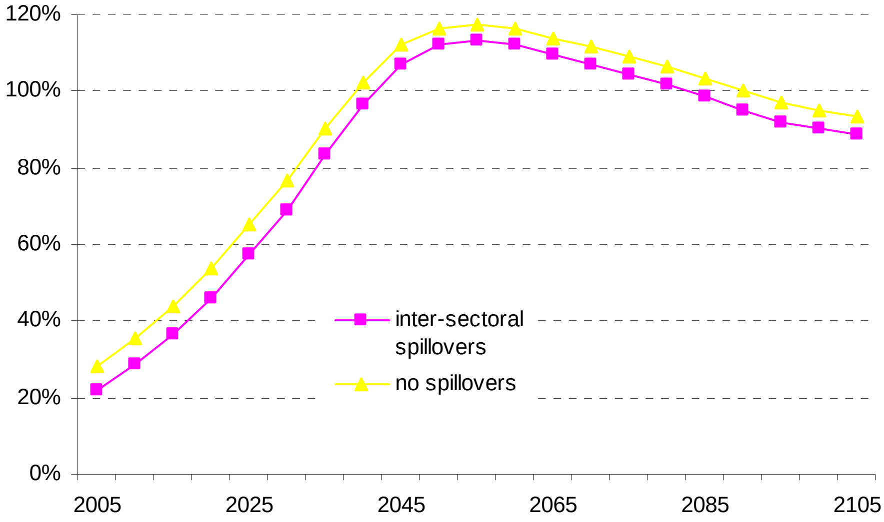

Figure 3. Percentage change of Investments in Energy R&D: stabilization wrt bau

When we model intersectoral spillovers, we find that the effect of climate policy is confirmed but Energy R&D increases less and Non-Energy R&D decreases less with respect to the model without knowledge externalities. Since the Non-Energy R&D sector is much larger than the Energy R&D sector this implies that total R&D investments decline less when intersectoral spillovers are modelled. It is important to stress that this result is obtained in a solution framework in which knowledge spillovers are a pure externality.

As a result, climate policy costs -measured as the ratio of discounted policy-induced GWP loss over discounted GDP in the BaU scenario- is equal to 1.66% when spillovers are not accounted for and to 1.50 when spillovers are modelled. This implies that not modelling intersectoral knowledge flows leads to an overestimation of policy costs of about 10%. This result is remarkable and has not been shown before in the literature.

	No Spillovers	Spillovers	Stabilization Policy and Spillovers Internalized
Energy R&D Investments	99%	94%	895%
Non-Energy R&D Investments	-10%	-8%	-2%
Total R&D Investments	-9%	-7%	5%

Table 3. The climate policy induced change in R&D investments, 2005-2105.

	No Spillovers	Spillovers	Stabilization Policy and Spillovers Internalized
Stabilization Cost	1.66%	1.50%	0.98%

Table 4. The Cost of the Stabilization Policy

Costs are measures as the ratio of discounted GDP losses to discounted GDP in the BaU scenario. We use a discount rate of 3% which declines over the century.

The final exercise we present in this paper considers a world in which both externalities –the environmental and the knowledge one– are internalized. This is of course a very idealized world but it permits to assess what are the implications of market failures in the R&D sector in terms of innovation dynamics and output losses, when a stringent climate policy is implemented. Table 2 displays the impact on R&D investments. We can see that when spillovers are internalized, energy R&D increases eight-fold when a cap on emissions is imposed. This results in a tremendous expansion of the energy R&D sector. Most interestingly, the Non-Energy sector contraction is more modest and as a result overall R&D spending in the economy increases when the climate policy is imposed.

Stabilization costs, shown in Table 3, are 35% lower when both externalities are addressed. Thus, it emerges that policies that contrast market failures in the R&D sector do not contrast with environmental targets. Quite the opposite, our study has shown the potential for powerful synergies.

Conclusions

With this study we have introduced intersectoral knowledge spillovers in a version of the WITCH model with directed technical change. In our modelling framework R&D investments can be used to increase the productivity of the Energy input as well as to enhance the yield 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. By doing so, we do not arbitrarily change the dynamics of knowledge accumulation displayed by the WITCH baseline scenario. Instead, we calibrated the model with knowledge spillovers in order to reproduce economic, technological and environmental dynamics of the model without explicit knowledge spillovers. This allows us to understand what are the implications of modelling intersectoral knowledge spillovers on R&D accumulation dynamics and on stabilization costs when a climate policy is imposed.

We have shown that the stabilization of CO_2 concentrations at 450ppm (550 all GHG) Energy R&D investments increase less and Non-Energy R&D investments decrease less when intersectoral knowledge spillovers are modelled. Nevertheless, we still reproduce the result found in Carraro, Massetti and Nicita (2009) that the climate policy induces a contraction of total R&D spending.

Quite remarkably, we find that when intersectoral spillovers are modelled the costs of the stabilization policy drop by almost 10%. This finding has important implications particularly for the modelling community and fosters the adoption of a better description of knowledge dynamics in integrated assessment models used to evaluate climate policies.

Finally, we have shown that total R&D increases under a climate policy if there is a commitment to internalize domestic knowledge externalities. By internalizing both knowledge spillovers and the environmental externality, we have shown that it is possible to reduce stabilization costs by 35% with respect to a stabilization scenario in which R&D social benefits are not fully internalized.

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Appendix A: 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:

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

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

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

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:

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

Where *j* denotes energy technologies.

Output is produced via a nested CES function that combines a capital-labor aggregate and energy; capital and labor 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:

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

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:

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

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

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

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

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

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

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

Final good capital accumulates following the standard perpetual rule:

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

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 $HE(n,t)$:

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

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

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

The two knowledge stocks evolve as follows:

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

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

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

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

Capital for electricity generation technologies accumulates as follows:

$$K_j(n,t+1) = K_j(n,t)\left(1-\delta_j\right) + \frac{I_j(n,t)}{SC_j(n,t)}\ , \tag{A15}$$

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:

$$SC_j(n,t) = B_j(n) \sum\nolimits_t \sum\nolimits_n K_j(n,t)^{-\log_2 PR_j}\ . \tag{A16}$$

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:

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

where Q_f is cumulative extraction of fuel *f*:

$$Q_f(n,t-1) = Q_f(n,0) + \sum\nolimits_{s=0}^{t-1} X_{f,extr}(n,s)\ . \tag{A18}$$

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.

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

Climate Module

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:

$$CO_2(n,t) = \sum\nolimits_f \omega_{f,CO_2} X_f(n,t) - CCS(n,t)\ . \tag{A20}$$

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

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

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

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

The damage function impacting output varies with global temperature:

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

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:

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

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

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