The interaction between carbon and technology policies

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1. Climate and Innovation Policies

The difficulty of protecting the environment at low economic cost and without harnessing economic growth has stimulated an increasing debate on the role of technical progress and on the prospective achievements of technological innovation. In particular, in the case of climate change, it is now widely recognized that, without some drastic innovations in the energy and transport sectors, the world future economic development can hardly be sustainable.

There are several aspects of technological innovation that affect the interactions and links between economic growth and climate change control. In some cases, the effect of innovation is straightforward. Innovation reduces GHG emissions per unit of output, lowers abatement costs, and facilitates the introduction of climate-friendly processes and products. In other cases, the effect of innovation may be indirect. Innovation and the resulting investment in new and improved processes of production enhance economic growth and increases GHG emissions. This negative effect may partly offset the previous positive direct impact on emission reduction. Finally, innovation has important effects on international competition, as it modifies the pattern of geographical distribution of industrial activities and thus the incentive to locate plants in countries with lower environmental standards. This is also important for climate policy, because it modifies leakage effects and the pattern of trade, with relevant implications on the incentives to reduce GHG emissions and on the international distribution of these emissions.

Both climate and innovation policy aims at correcting some market failures but may be undermined by other market failures. In particular, three types of market failure should be addressed by a climate-related innovation policy. The first is the conventional market failure associated with externalities. If innovation results developed by one firm spillover to other firms, there is an incentive for firms to distort and/or to undersupply their innovation effort. The second is the conventional *static* market failure associated with imperfect competition - typically output is too low, prices too high, and there is excessive entry. The third is the *dynamic* market failure surrounding R&D and innovation. It arises fundamentally from the nature of knowledge as a public good, which is expensive to produce, but cheap to reproduce. It is particularly important for basic research, but it also holds for applied research. When studying the interactions between climate and innovation policy it is therefore important to take into account the aforementioned market failures that may drastically reduce the effectiveness of innovation measures designed to complement climate policy.

It may be argued that climate policy is itself an innovation policy. Climate policy, by introducing and modifying the price of carbon, modifies the incentives to innovate and may spur climate-friendly innovation. As shown by Ulph, D. (1997), there are two main effects of climate policy – whether cap and trade, carbon taxes or standards – on innovation. The first effect is to alter the effectiveness of R&D in lowering costs. A second, indirect, effect of the policy is to change the value to the firm of lowering costs. These effects go into opposite directions, though the sign depends on the nature of the policy instrument. A carbon tax or a system of tradable permits has a positive direct effect and a negative indirect effect, whereas standards have a negative direct effect and positive indirect effect. These conclusions are very general and do not depend greatly on the nature of either product market competition or R&D competition (Cf. Ulph, D. 1997).

However, the balance between the two effects does depend on the nature of R&D competition. Hence, in non-tournament models of innovation, it will typically be the case that higher carbon prices or taxes will stimulate R&D, whereas in tournament models of innovation the balance between the effects depends sensitively on the competitiveness of the product market (Cf. Jaffee and Stavins, 1995; Jung, Krutilla and Boyd, 1996).

Therefore, climate policy could have a limited effect on innovation. And if it does have an effect, it may not be sufficient to mitigate total GHG emissions. Or, alternatively, it may increase climate-friendly innovation at the expenses of other forms of R&D and innovation. This crowding-out issue is stressed by Goulder and Schneider (1996), whose theoretical model explicitly accounts for the possibility that increased investment in R&D by one sector (e.g. the alternative fuels sector), by demanding scarce knowledge-generating resources, might "crowd-out" investment in R&D by other sectors. To the extent that such crowding-out occurs, rapid technological change in one sector will be accompanied by less rapid change in other sectors.

For all the above reasons, the proposal to complement climate policy with a technology or innovation policy must be carefully examined. Even though the direct effect of a technology policy that explicitly addresses the delays and inefficiencies induced by market failures in the innovation sector may be beneficial, there are many secondary indirect effects that may offset the benefits of the main direct one. Therefore, technology policy must be carefully designed to avoid crowding-out effects and negative interactions with climate policy.

Summing up, policies designed to stimulate technological innovation and to favour its diffusion are likely to be necessary if GHG emissions are to be reduced sufficiently in the coming years. How can the systemic effects of carbon and innovation policies be evaluated? Are their interactions synergic? Or do crowding out effects and/or output growth effects and/or leakage effects prevail? In order to answer these complex questions, it is crucial to model the interactions of climate and innovation policies at the international level. To do this, climate economy models must be appropriately modified and improved.

2. The role of technical change in climate-economy models

Climate-economy models used to quantify the costs and the effects of climate change impacts and policies have become an important tool to assist climate change policy analysis. In the context of climate change, where the time horizon at stake is a century or more, a careful characterization of the long run dynamics is a key element for the accuracy of the forecasts. The way technological change evolves over time and the possibility for policy makers to affect its speed and direction is a key element of long run dynamics.

The specification of the dynamics of technical change in economy-climate models has received increasing interest from climate-economy modellers. Technological change has always been included in quantitative models, though in an unsatisfactory way. The first generation of climate-economy models included the time evolution of technical change, but its determinants were left exogenous, reflecting the pattern of historical data. Technical change, which is actually an unobservable variable, was often approximated by a deterministic time trend (Nordhaus and Yang, 1996). This approach paved the way for other models in which technical change was described as a stochastic trend (Boone and others, 1992, Carraro and Galeotti, 1996).

Such a trend was not just a function of time, but also of other economic variables. The limits of these models are the lack of a theory explaining the link between the technological trend and other economic variables, which relies mainly of the statistical evidence.

More recent modelling efforts have focused on a more comprehensive description of technical change and a large number of models with endogenous and/or induced technical (ETC/ ITC) change have been emerging. Despite being a latent variable, technical change is deeply rooted in the economic environment and therefore can be related to other economic variables. Different types of models have implemented ETC/ITC using different technical devices. The choice of the approach depends on the structural features of the models. A long-standing distinction in economy-environmental modelling distinguishes between Top-down and Bottom-up models. This distinction is becoming increasingly blurred and efforts aimed at combining features of both models are increasing, leading to the development of hybrid models. Still it is useful to describe the structural differences between these two groups of models, distinguishing between Top-down and Bottom-up features. Whereas the second group (Bottom-up) focuses on a detailed description of technological aspects, the first group (Top-down) of models pays more attention to the macroeconomic dimension of socio-economic systems. In concrete terms, Top-down and Bottom-up models differ mainly with respect to the representation of the energy system and its interactions with the rest of the economy.

Top-down climate-economy models provide a theoretically consistent description of the general economy and of the major macroeconomic variables. They can be broadly classified into intertemporal optimizing growth models and computable general equilibrium models (CGEs). Most intertemporal growth models build upon the theoretical Ramsey-Koopmans neoclassical growth framework, where the economy equilibrium is solved through intertemporal optimization of the representative agent's utility function. Given the complexity of the optimization process, they tend to have a simplified description of the economic system, which is condensed into one final good. The growth dynamic is driven by capital accumulation in the framework of intertemporal social welfare maximization. A natural extension of these climate-economy models is the inclusion of R&D investments and knowledge accumulation, along the theoretical developments of endogenous growth theory.

CGE models are Arrow-Debreu models where the demand and supply of multiple sectors balance. The equilibrium is determined by simultaneous clearance of all markets. They are multi-region, multi-industry models where output is produced in competitive regional markets. Therefore, they are suitable for the analysis of market interactions and sectoral reallocations following a change in relative prices. They can describe how a price change in one sector (e.g. change in the fossil fuel price following the introduction of climate policy) has second order effects on all other sectors of the economy. Intertemporal dynamics have been included in CGEs in two ways: recursively or intertemporally. Recursive CGEs link static equilibria in a recursive path by specifying growth dynamics in between steps. Intertemporal CGEs compute the equilibrium by maximizing the discounted sum of utility and profits over the overall time horizon. In these models, in particular for global ones, the specification of technical change is often the usual exogenous one.

Bottom-up climate-economy models are linear activity models that compute the cost-minimising mix of energy technologies for an exogenously given energy demand, subject to a set of carbon emissions constraints using linear programming. These models are based on engineering information about technical coefficients and parameters, describing a large number of specific technologies. The advantage of such a detailed representation of the energy sector is the ability to base technological change on the costs and performance of different technologies. Their limit, however, is the partial equilibrium perspective. Some models have addressed such limitation combining a bottom up description of the energy sector with a model of the general economy. For example, MESSAGE (Messner, 1997) and MARKAL (Barreto and Kypreos, 2002) are models of the energy sector that are generally used together with MACRO, a macro-economic model which provides economic data for the energy sector. Given the detailed description of technologies, these models can explicitly introduce a relationship between technology costs and the cumulative capacity installed, also referred to in the literature as learning or experience curve. This is another approach to technological change, in which technology improvements are assumed to be a side effect of the economic activity.

The classification of climate-economy models in these two categories is by no mean exhaustive. Of increasing importance are models that merge features of both Top-down and Bottom-up models, known in the literature as hybrid models. Such models integrate a macroeconomic framework with a detailed bottom-up description of the energy sector. For example, MERGE (Manne and Richels, 1992) is an intertemporal model which merges nine ETA-MACRO regional sub-models. Each of the nine regions is described by an economic regional macroeconomic growth model (MACRO). Moreover, each region has a bottom-up representation of the energy supply sector that produces electric and non-electric energy (ETA). Aggregate final output is produced with a constant elasticity production function using labor, capital and energy. Another recent hybrid top-down climate-economy model is WITCH (Bosetti, Carraro, Galeotti, Masetti and Tavoni, 2006; Bosetti, Masetti and Tavoni, 2007). Besides linking climate policy and macroeconomic performance, it has a very detailed energy sector breakdown. WITCH is a neoclassical growth model encompassing 12 regions interacting with each other in a game-theoretic set up. In addition, the energy sector has a very detailed representation and, contrary to MERGE which links two separated models, it is fully integrated in the economic model. Energy includes both electric and non-electric energy, each of which has a further detailed disaggregation.[1] In this model, therefore, both learning curves and R&D investments are endogenised and affect the efficiency of production inputs and energy technologies.

It is then clear that the design of the model structure affects the technical possibilities to represent endogenous and/or policy-induced technical change. Bottom-up models are traditionally associated with experience curves, whereas R&D investment and knowledge accumulation have been implemented mostly in Top-down macroeconomic models. In optimal growth models, technical change is represented as a process of efficiency improvement or/and of cost reduction. Such process can be exogenous or endogenous, i.e. inputs are augmented with coefficients representing their efficiency in production, which can evolve over time exogenously or endogenously. By contrast, large CGE models with many countries and many sectors, such as the EPPA model (Paltsev et al., 2005), typically assume exogenous total factor productivity and includes an exogenous time trend in the energy input coefficient, called autonomous energy efficiency improvement (AEEI).

Learning by Doing (LbD) versus Learning By Researching (LbR) are the two major mechanisms used by climate-economy modellers to introduce

[1] For a more exhaustive review on the hybrid modelling literature see "Hybrid Modelling: New Answers to Old Challenges Introduction to the Special Issue of The Energy Journal", Hourcade, Jean-Charles; Jaccard, Mark; Bataille, Chris; Ghersi, Frédéric. *Energy Journal*, Hybrid Modelling of Energy-Environment, Vol. 27, p. 1-11.

endogenous and/or induced technical change. They are based on theoretical models that acknowledge two sources of technological change: experience and innovation. Learning by doing is associated with the experience occurring over time with the repetition in the use or in the production of the same activity. Learning by researching instead refers to the knowledge accumulation brought about by R&D expenditure. Whereas R&D investments have an opportunity cost and reduce the availability of resources for alternative uses (crowding-out effect), LbD is costless and it is a side effect of economic activity.

LbD and LbR capture two different types of learning process and a complete description of the process of technological change should envisage both. An approach toward LbD and LbR as complements rather than substitute has been emerging and is increasingly more difficult to find models that rely exclusively on LbD or LbR. Without forgetting that another potential source of endogenous technical change are international technology spillovers. The theoretical setup is the model developed by Grossman and Helpman (2001), who emphasized the role of international trade for domestic growth. Spillovers occur indeed through trade movements, but also through capital movements, FDIs and the existence of a freely available pool of knowledge.

Notice, that the way technical change is implemented affects the costs and the timing of climate policies. For example, models incorporating endogenous technical change via LbD tend to favour early carbon abatement, as the costs are driven down with the accumulation of the experience. On the contrary, models relying on R&D investments tend to predict a delay in the abatement activity. Moreover, if R&D is directed toward the energy sector, it may crowd out aggregate R&D, with a negative overall effect on GDP. As another example, the mitigation costs of energy system models tend to be lower because they do not include rebound or general equilibrium effects. Moreover, by including a multitude of technologies, they tend to overestimate the substitution possibilities.

We can therefore conclude that an ideal climate-economy model should be a hybrid model that accounts for both LbD and LbR effects, and for technology spillovers. In addition, these effects should be endogenous and depend on policy decisions, in particular climate and technology policies. This is the case of WITCH, the model used in section 4 to carry out some numerical experiments to evaluate the interactions between climate and innovation policy.

3. The WITCH model

The WITCH model allows us to represent both the Bottom-up and the Top-down dimension of endogenous technological change. As for the Top-down component, in WITCH energy R&D increases the overall efficiency of the energy system, similarly to Popp (2004a). LbD instead decreases wind and solar power plant investment costs in proportion to the accumulated installed capacity.

WITCH is a Ramsey-type neoclassical optimal growth hybrid model defined for 12 macro regions of the world. For each of these regions a central planner chooses the optimal time paths of the control variables – investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels – so as to maximize welfare, defined as the regional present value of log per capita consumption. WITCH is a truly dynamic model in the sense that at each time step forward-looking agents simultaneously and strategically maximize with respect to the other decision makers. Therefore, the dynamic profile of optimal investments in different technologies is one of the outcomes of the model. These investment strategies are optimized (non-cooperatively) by taking into account both economic and environmental externalities (future climate damages). The investment profile for each technology is thus the solution of an intertemporal non-cooperative game between the 12 regions. From a top-down perspective, WITCH enables us to analyze both the geographical dimension (e.g. rich vs. poor regions) and the time dimension (e.g. present vs. future generations) of climate policy.

Like Bottom-up models, WITCH contains a detailed representation of the energy sector. It separates electric and non-electric uses of energy, features seven power generation technologies and includes the use of multiple fuels: oil, natural gas, coal, uranium, traditional biomass and biofuels. This kind of detail in the energy sector – although still much simpler than that of large scale energy system models – is a novelty for this class of models and enables us to reasonably portray future energy and technological scenarios and to assess their compatibility with the goal of stabilizing greenhouse gas concentrations. Also, by endogenously modelling fuel prices, as well as the cost of storing the captured CO_2, we are able to evaluate the implications of mitigation policies for all the components of the energy system.

Following recent research in climate modelling (see, for example, the 2006 special issue of the Energy Journal on the IMCP Project), technical change in WITCH is endogenous and can be induced by climate policy, international spillovers and other economic effects. In the bottom-up part of the model, WITCH encompasses the Learning-by-Doing effects by bringing in experience curves for all energy technologies, while, in the top-down part, the accumulation of knowledge (via R&D) and its effects on energy efficiency and the cost of advanced biofuels are accounted for.

In WITCH, countries/regions are exposed to a pool of world knowledge that can be considered as a global public good. A fraction of this knowledge is absorbed by each country and is available for use in the domestic R&D sector. Therefore, WITCH can accommodate the effect of disembodied knowledge spillovers by introducing a transmission channel across energy R&D sectors and across regions. The implications of these spillovers for investments in the creation of new ideas, climate policy costs and energy demand can all be analyzed (see Bosetti, Carraro et al. 2008).

We assume indeed that only a fraction γ of the world's available pool of knowledge is absorbed by each country. The absorption parameter γ might be an indicator of industrial policy or of the legal environment, or a measure of some effort to absorb international knowledge. We consider γ as being primarily a function of domestic knowledge. In this, we follow Cohen and Levinthal (1989), who were the first to suggest that the process of learning, far from being free, is costly and that most of this cost is borne by a stock of knowledge cumulated in the receiving country. Keller (2004) reinforces this position in his survey of international knowledge spillovers, by showing that an R&D effort is needed to absorb international knowledge. By means of an empirical analysis of spillovers across OECD manufacturing industries, Kneller (2005) finds that absorptive capacity, rather than physical distance, plays an important role in determining the amount of knowledge transfers at the international level. Accordingly, we assume that the absorption capacity $\gamma(n,t)$ is a function of the distance of R&D capital accumulated in the region with respect to the *technological frontier*. The further one country lies from the *technological frontier*, the lesser this country is able to absorb knowledge from the potentially available international knowledge pool. In words, the lack of laboratories, scientific bodies, investments in

R&D in developing countries is a serious obstacle to the profitable use of the knowledge that circulates in the world.

Notice that, in our framework, the public good features of the knowledge pool are somehow mitigated. Were knowledge a fully global public good, the incentive to free-riding would dominate, regions would invest less in technology R&D and the overall production of knowledge would shrink.[2] On the contrary, by giving knowledge a role in the process of knowledge absorption and by letting international R&D spillover augment the productivity of domestic investments, we have introduced forces that work against the free-riding incentive. This is in accordance with the literature on knowledge spillovers. As an example, Cohen and Levinthal (1989) have shown that when domestic R&D increases absorption capacity and some general conditions hold, the incentive to invest more in R&D offsets the disincentive represented by free-riding, and world investments in R&D eventually increase.

4. The Interaction between Climate and Technology Policies. Some Results

The WITCH model enables us to assess the importance of free-riding incentives and of the various channels through which innovation policy is transmitted to the economic system. The presence of free-riding effects induced by knowledge spillovers enables us to capture the market failures previously identified. In addition, in the model, energy R&D investments play a twofold role. On the one hand, they increase energy efficiency and therefore reduce the intensity of GHG emissions; on the other hand, energy R&D investments enhance economic growth. Therefore, at the equilibrium, these R&D investments may not be sufficient to control climate change or stabilization of GHG concentrations may be achieved at high costs. It is then important to study how stabilization costs change when the endogenously determined energy R&D is complemented by a public R&D scheme, designed to stimulate energy R&D investments(on this issue, see also Bosetti, Carraro et al. 2009).

[2] The standard result that sees free-riding effects to dominate has also been questioned by D'Aspremont and Jacquemin (1988), who show how, in a cooperative setting with strong knowledge flows, spillovers induce higher overall investment in R&D due to the full internalization of positive externalities.

To analyze this issue, let us consider a stabilization policy in which a global cap-and-trade scheme is adopted to stabilize emissions at 450 ppmv (CO2 only). Allowances are freely distributed according to an equal per capita criterion. Then, assume that a technology policy is adopted to complement the cap-and-trade climate policy. The technology policy is defined as an additional publicly funded investment in energy R&D in all regions. Financial resources come from sharing an international fund devoted to energy R&D investments. This fund is created by having all regions devoting an exogenously given share of their GDP, and it is then redistributed on the basis of equal per capital shares (this provides additional incentives for developing countries with low absorptive capacity).

To estimate the percentage of GDP that should be devoted to establishing an international fund to subsidize energy R&D, we proceed by calculating the amount of energy R&D that would be optimal in a fully cooperative world, when a stabilization policy is imposed (450ppm CO2 only). In this scenario, all externalities are obviously fully internalized.

Let us briefly describe the results obtained using WITCH. As expected, world energy R&D investments in the cooperative solution are indeed higher than in the non-cooperative solution – albeit the difference is not very large. Over the century, in a fully cooperative world, the investments in energy R&D are 6.2% higher than in a non-cooperative world. Total investments in energy R&D in a cooperative world would reach approximately 764bn US$ (discounted at 5%), while in the non cooperative case energy R&D investment would be approximately 719bn US$.

This difference is accentuated in the second half of the century. Several empirical findings suggest rather that endogenous technical change usually increases the benefits of earlier action, which accelerates the development of new technologies. These findings rely however on a representation of technological change through learning by doing – which would indeed call for early deployment of capacity in order to lower the price of the technology. In our case, R&D improves energy efficiency, and it does not affect directly the cost of the technologies.

Interestingly, in the fully cooperative world, Non-OECD countries invest more in R&D at the beginning of the century, whereas the opposite is true for OECD countries. Overall, Non-OECD countries invest about 506 US$ bn more in R&D in the cooperative case (55bn discounted at 5%), whereas

OECD countries a mere 90bn (with a 5% discount rate, total R&D investments in OECD countries over the whole century actually decrease, as most of the additional investment is done after 2060). This can be explained by the fact that, in an ideal world (WITCH is an optimization model), non-OECD countries should invest more in the short-term in order to increase their absorptive capacity and, therefore, the future magnitude of spillovers.

To put these figures into perspectives, let us compare the additional R&D investment to major proposals for technology research. For instance, the ITER project – a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power – is estimated to cost 4.57bn€ (at 2000 prices), to be spread over about ten years. Estimated total operating costs over the expected operational lifetime of about twenty years are of a similar order. The total cost over the period 2005 to 2035 is therefore expected to be approximately 13.7bn €. Over the same time period (2005 to 2035) additional R&D in our scenario amount to 26bn US$ (US$ 1995 prices, discounted at 5%).

Let us analyze the implications of the proposed combined climate and technology policy (cap and trade plus R&D subsidy). With the additional R&D subsidy, the stabilization policy is less costly in terms of both global and regional GDP, though the reduction in the policy costs is negligible (-0.18%). This cost difference is measured with respect with the cost of stabilization in the case in which only a cap-and-trade carbon policy is adopted. The limited impact may be attributed to the relatively small fraction of GDP that regions devote to subsidize R&D. However, it may also be explained by the importance of market failures in the model, by the growth enhancing role of R&D investments and/or by crowding-out effects in the energy R&D sector.

Let us analyze this issue in more detail. The difference in global R&D investments, discounted at 5%, again with respect to the case in which there is only a cap-and-trade carbon policy, is 4.3bn US$, that is, only 0.6% of global energy R&D efforts are induced by the financial transfers of energy R&D. This compares to the total subsidy of 44bn – indicating that the international fund may decrease the incentives to invest in energy R&D.

When we compare the autonomous investment in energy R&D – that is, the investment in R&D over and above the resources provided through the cooperative pool of resources – that OECD and non OECD countries undertake in this scenario, to the investment that the two regions would make without the R&D fund, we observe a marked decline. The implication is that the additional publicly funded R&D transfers crowd-out regional investments in R&D. The crowding-out effect is stronger in non-OECD countries.

Therefore, crowding-out effects seems to reduce the effectiveness of this particular form of R&D subsidy. In order to offset crowding-out effects, let us impose an additionality constraint on recipient countries, that is, the international R&D subsidy is subordinate to a minimum investment in energy R&D by each region. To assess the implications of this formulation of the technology policy, we impose into the model a new constraint, forcing regions to invest at least as much as they would invest without the R&D cooperative fund.

As in the previous case, when we consider GDP as a metric, the joint carbon and technology policy lowers the cost of stabilisation with respect to the case in which only a cap-and-trade policy is adopted, but again by a negligible amount (-0,36% of global GDP). Impacts on consumption possibilities are larger, with Non OECD regions benefiting more than the OECD. However, in this policy scenario, the OECD is much better off than when no additionality constraint is imposed. Intuitively, non-OECD countries can no longer substitute the majority of their own investment in R&D with the international transfers. The pool of world knowledge is thus significantly increased, and OECD countries can also enjoy the benefits of higher knowledge spillovers. The overall energy R&D effort is thus significantly higher than under the previous policy scenario (+44.8bn US$ over the century using the 5% discount rate).

Therefore, a combined climate and technology policy that neutralises crowding-out effects is indeed able to enhance R&D investments, even though the cost of GHG stabilization is only slightly reduced. In other words, the proposed policy neutralises both free-riding (because the R&D investment profile coincides with the optimal one) and crowding-out (because subsidized R&D is additional to the existing one) effects. Nonetheless, the effect on policy costs is small. The remaining explanation is the twofold role of R&D investments. The improvement of energy efficiency induced by additional R&D investments, and the consequent reduction of GHG emissions, is almost completely compensated by the enhanced economic growth. This also suggests that it would be better to subsidize deployment of existing low carbon or new carbon free technologies, that enjoy enjoy LbD, and can therefore enhance the effectiveness of climate policy.

5. Conclusion

This paper has examined the interactions between some carbon and technology policies. Previous theoretical contributions had emphasised that climate and technology policies may not be fully synergic. Two main reasons were underlined. On the one hand, growth-enhancing effects of R&D investments and technology expenditures may stimulate economic growth and thus GHG emissions. On the other hand, climate-related R&D and innovation investments can crowd-out other types of investments (e.g. R&D in other sectors). This reduces the former growth-enhancing effect, but also modifies the speed and direction of technological innovation, and may increase GHG emissions. The effectiveness of climate-related technology policies may also be reduced by spillover effects and other market imperfections.

Our model results support the above theoretical possibilities. By using WITCH, a hybrid climate-economy model of the world economic system, we have computed the effects of an integrated carbon and technology policy in which a cap-and-trade scheme is combined with an additional public expenditure scheme for climate-related R&D designed to improve overall energy efficiency. We have shown that this policy only slightly reduces the costs of stabilising GHG emissions, because higher R&D investments actually improve energy efficiency, but also stimulate economic growth.

This calls for a careful examination of future technology and climate policies, which may focus more on the deployment of low carbon or new carbon free technologies than on energy efficiency innovation (see Bosetti, Carraro and Tavoni, 2009). A more comprehensive analysis of different technology policy schemes associated to different climate policy instruments would be necessary to provide some general and robust policy recommendations.

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