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ABSTRACT

Human Capital, Innovation, and Climate Policy: An Integrated Assessment

This paper looks at the interplay between human capital and innovation in the presence of climate and educational policies. Using recent empirical estimates, human capital and general purpose R&D are introduced in an integrated assessment model that has been extensively applied to study the climate change mitigation. Our results suggest that climate policy stimulates general purpose as well as clean energy R&D but reduces the incentive to invest in human capital formation. Human capital increases the productivity of labour and the complementarity between labour and energy drives its pollution-using effect (direct effect). When human capital is an essential input in the production of generic and energy dedicated knowledge, the crowding out induced by climate policy is mitigated, thought not completely offset (indirect effect). The pollution-using implications of the direct effect prevail over the indirect contribution of human capital to the creation of new and cleaner knowledge. A policy mix that combines educational as well as climate objectives offsets the human capital crowding-out with a moderate, short-term consumption loss. Human capital is complement to all forms of innovation and an educational policy stimulates both energy and general purpose innovation. This result has important policy implications considering the growing concern that effective climate policy is conditional on solid economic development and therefore it needs to be supplemented by other policy targets.

JEL Classification: O33, O41, Q43
Keywords: climate policy, human capital, innovation, sustainable development

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1. Introduction

An increasing number of integrated assessment models used in climate change policy analysis have looked at the dynamics of technical change. Models describing technical change as an endogenous process make it possible to study the relationship between climate policy and technical change and to evaluate the implications of policy-induced technical change (ITC) on the macroeconomic costs of climate policy. A first wave of studies focused on innovation in the energy sector, the reason being the relevance of energy efficiency measures and decarbonisation of energy as mitigation strategies (Nordhaus 2002, Popp 2004, Bosetti et al. 2006). These models assume that technical change is necessarily energy-saving, neglecting other forms of innovation or technical change that could actually have an energy-using effect (see for example Managi and Kumar 2009, Carraro and De Cian 2009). This approach encounters the risk of underestimating the costs of climate policy because it overlooks the macroeconomic dynamics of technical change and cannot track how climate policy redistributes resources across different R&D sectors.

An increasing number of climate-economy models now features both energy–saving and energy-using endogenous technical change (Goulder and Schneider 1999, Sue Wing 2008, Otto et al. 2007, Gerlagh 2008, Carraro et al. 2009, Massetti and Nicita 2010). These models share the idea that technology advancements in both energy- and non-energy sectors are driven by a specific stock of knowledge. They all agree that climate policy modifies not only the direction of technical change, but also the total level of innovative activity. Goulder and Schneider (1999), Sue Wing (2008), and Otto et al. (2008) emphasise how the general equilibrium effect due to the policy-induced income reduction can lower the overall amount of resources available for knowledge creation. Gerlagh (2008) shows that if a sufficient amount of investments go to energy-saving technical change, then there might be a research dividend and overall research activity may increase. Carraro, Massetti and Nicita (2009), Massetti and Nicita (2010) highlight that the complementarity between energy and non-energy inputs drives the direction of induced technical change, in line with theory of directed technical change (Acemoglu, 2002).

Guided by the empirical evidence on induced innovation (Lanjouw and Mody 1996, Jaffe and Palmer 1997, Newell, Jaffe and Stavins 1999 and Popp 2002) and following mainstream growth theory (e.g. Arrow 1962, Romer 1986 and 1990, Grossman and Helpman 1991, Aghion and Howitt 1992, Acemoglu 2002, Acemoglu et al. 2009), most climate-economy models assume that the engine of technical change is the accumulation of knowledge or experience. Other drivers such as human capital (Lucas 1998, Blankenau and Simpson 2004) or trade (Cameron 2005, Managi and Kumar 2009, Carrao and De Cian, 2009) have been neglected. The narrow focus on energy R&D has bounded the applicability of IAM to the study of clean innovation in relation to climate change.

By omitting other engines of macroeconomic growth, the connections with economic development have not been fully analysed by the modelling literature. The aim of this paper is to explore this linkage and provide some novel insights on the connections between climate change and economic development, with a particular focus on education.

Climate change policy and education can interact through several channels. First of all, a higher level of human capital can make mitigation policies more effective. Human capital is an essential input in the creation of new knowledge and new products and therefore it is behind energy-saving innovation as well. Better skills can be expected to lead to a faster development of technologies that can replace or reduce the use of fossil fuels. Some studies do support the existence of a positive relationship between innovation and human capital, but at the aggregate level (Griffith, Redding, and Van Reenen 2000, Teixeira and Fortuna 2004). To our knowledge, there are no empirical works that have looked at the relationship between knowledge and human capital in the context of climate-related innovation. By stimulating labour productivity and economic growth, expenditure in education can increase the amount of resources available for productive usages, including innovation. Human capital is positively related to the capability of adopting cleaner technologies ((Nelson and Phelps 1966) developed under the stimulus of environmental policy. Education can also be expected to improve the effectiveness of adaptation measures. The Third Assessment Report of the IPCC identified human capital among the determinants of adaptive capacity. According to Yohe (2001) human capital not only affects the ability to respond to climate variability and change, but it is also a determinant of mitigative capacity. Finally, education is fundamental to increase the awareness of climate change, which in turn should increase the willingness of voters to support climate policy. The achievement of universal primary education is one of the eight Millennium Development Goals, to be achieved by 2015, together with sustainable development. The question we ask in this paper is whether there are synergies between educational and climate change policies that go through the innovation and growth channels.

Our starting framework is an integrated assessment model with a good characterisation of endogenous technical change, but confined to the energy sector (Bosetti et al. 2006, 2009). We amend the macroeconomic production structure to account for factor-augmenting effect of general purpose R&D and human capital. This introduces a *direct* link between human capital and economic growth. In this setting, the distributive effects of policy in different forms of expenditure and innovation can be fully characterised. We also look at the *indirect effect* that human capital could have on technology absorption and innovation, though as an explorative analysis aimed at identifying areas for future research. The paper proposes a comparative analysis of climate policy under three model variants that enable us to evaluate how the induced-technical change hypothesis responds to different representations of technical change. The more general treatment of endogenous technical change allow us broaden the focus of the analysis from the narrow climate policy-energy-innovation link to the climate change and economic development nexus.

Our results indicate that climate policy stimulates dedicated investments in energy R&D without reducing general purpose innovation. On the other hand, education expenditures are reduced, penalising the formation of human capital. What drives this result is the assumption that human capital is pollution-using because it augments the productivity of labour, which is gross complement to energy. The crowding-out of climate policy on education expenditure is lessened if resources allocated to education can foster technology absorption and innovation.

We also find that human capital is complement to all forms of innovation. A policy that sustains education expenditure stimulates both energy and generic innovation. This implies that a policy mix that combines a climate stabilisation target with an educational policy sustaining education expenditure could reduce the long-run macroeconomic costs of the climate policy. The additional costs of implementing the two policies are transitory and in the long-run a scale effect partly mitigates climate change policy costs.

The rest of the paper is organised as follows. Section 2 describes the relationship between technical change and input substitution when technical change is factor-specific. Factor-augmenting technical change, driven by innovation and human capital, is then incorporated into an Integrated Assessment Model. Policy scenarios are analysed in Section 3 and 4. Section 5 concludes.

2. Factor-augmenting technical change and IAMs

2.1 Factor-augmenting technical change and input substitution

Nearly all IAMs describe production using Constant Elasticity of Substitution (CES) production functions. Consider the simplest example of CES production function between labour (L), capital (K), and energy (EN)[1]:

$$Y(t) = H(t)(A_K(t)K(t)^{\frac{\sigma-1}{\sigma}} + A_L(t)L(t)^{\frac{\sigma-1}{\sigma}} + A_{EN}(t)EN(t)^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \quad (1)$$

where σ is the elasticity of substitution between the three inputs and (Y) is the final good produced in the economy, which can be used for consumption or investment. Factors of production are expressed in efficiency units. The multiplicative coefficients (A_i) represent the productivity of inputs. Neutral technical change is described by the parameter (H).

[1] The choice of a non-nested CES as opposed to a nest CES between a capital labour bundle and energy is not relevant for the results discussed in the paper. What ultimately drives the results is that non-energy inputs, capital and labour, are gross complements to energy.

Allowing for endogenous differences in the development of technology parameters has a theoretical foundation in the work on directed technical change (Acemoglu, 2002). When factor-augmenting technical change is endogenous, the effect of technology drivers can be both energy-using or energy-saving. Consider an endogenous formulation as estimated in Carraro and De Cian (2009), where capital and energy productivity depend on the stock of generic knowledge (*R&D)* while labour productivity depends on human capital (*HK)*:

$$\begin{aligned} A_K &= A_{K0} R\&D^{\chi_K} \\ A_{EN} &= A_{EN0} R\&D^{\chi_{EN}} \\ A_L &= A_{L0} HK^{\chi_L} \end{aligned} \tag{5}$$

With gross complementarity between factors of production ($\sigma < 1$) and positive elasticity of human capital on labour productivity, χ_L , *human capital has an energy-using effect*:

$$\frac{\partial\left(\frac{EN}{L}\right)}{\partial HK} = (1-\sigma)\chi_L \left(\frac{P_L}{P_{EN}}\right)^{\sigma} \left(\frac{A_{Lo} HK^{\chi_L}}{A_{EN}}\right)^{-\sigma} \left(\frac{A_{Lo} HK^{\chi_L - 1}}{A_{EN}}\right) > 0 \text{ if } \sigma < 1 \text{ and } \chi_L > 0 \tag{6}$$

As for R&D, the direct impact on energy demand is negative (e.g. energy-saving) if the elasticity of substitution is less than one. However, the indirect impact via capital productivity is energy-using, as in the case of human capital. The net effect ultimately depends on the relative size of the elasticity of capital and energy productivity with respect to knowledge, χ_K and χ_{EN}. Carraro and De Cian (2009) find that that $\chi_K < \chi_{EN}$, suggesting that overall *general purpose R&D has an energy-saving effect*. The next section describes how this formulation of technical change has been integrated in the integrated assessment model WITCH.

2.2 Factor-augmenting technical change and the WITCH model

Model enhancement

The WITCH model (Bosetti et al. 2006, 2007, 2009)[2] already provides a thorough characterisation of innovation, but only in the energy sector. WITCH is a regional integrated assessment, hard-link, hybrid model. Its top-down component consists of an intertemporal optimal

[2] A thorough description and a list of related papers and applications are available at http://www.witchmodel.org/.

growth model in which the energy input of the aggregate production function has been expanded to give a bottom-up like description of the energy sector. The model accounts for technological advances that can occur in the energy sector, distinguishing between the invention/innovation phase and the process of diffusion and deployment. The model distinguishes dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies (breakthrough technologies).

Starting from this set-up, we introduce endogenous technical change with input-specific technology drivers. We compare three model variants that differ in the way of accounting the role of human capital. The starting set-up (model 1) only considers the *direct* effect of human capital on labour productivity following the specification estimated in Carraro and De Cian 2009). The first variant (model 2) adds to the direct effect an *indirect* contribution via technology diffusion. In this case, human capital increases the absorptive capacity. The second variant (model 3) explores the relationship between human capital and innovation, adding the contribution of the *indirect* effect of human capital on knowledge formation. All model equations can be found in the Appendix. In the remaining of this section we describe model enhancement, calibration, and testing.

The macroeconomic production structure is modified to accommodate for factor-augmenting technical change with dedicated technology drivers (eq. A4). In the modified model, capital and energy productivities depend on a generic knowledge stock (the stock of general purpose R&D expenditure), whereas labour productivity on human capital (the stock of education expenditure), see eq. (A5). In addition to the effect of general purpose R&D, dedicated energy efficiency R&D can specifically address improvements in energy efficiency (eq. A5) or develop breakthrough technologies (eq. A11). Since the dynamics of technical change in all sectors are now endogenous, energy R&D investments compete with the resources that are allocated to human capital development and generic R&D.

The production of both human capital and knowledge is characterised by intertemporal spillovers. The stock available in each region at a given point in time contributes to the creation of the future stock. Following state-of-the-art literature (Romer 1990, Jones 1995, Popp 2002, Glomm and Ravikumar 1997, Blankenau and Simpson 2004) we assume that human capital is produced using a Cobb-Douglas combination of the existing stock of human capital and current expenditure in education. (eq. A6 and A7). In a similar way, the available knowledge stock and current R&D investments are combined to produce new knowledge (eqs. A8 and A9). The creation of energy knowledge is also influenced by international spillovers (see eq. A10). Foreign knowledge can impact domestic process of knowledge creation depending on country's absorptive capacity and distance from the frontier (Bosetti et. al 2008)[3].

In the two extended versions of the model these equations are modified to account for the indirect contribution of human capital. First of all (model 2), human capital increases the ability to adopt new technologies. This ideas goes back to the model of technology diffusion introduced by Nelson and Phelps (1966). Countries can benefit from the world technology frontier by incorporating more advanced technologies into their economy. Technology adoption is a human capital-intensive activity that requires skill labour. Therefore, a larger stock of human capital facilitates the absorption of new products and new discoveries. The idea that successful technology diffusion requires sufficient absorptive capacity (Cohen and Levinthal, 1990) has been empirically supported by a number of studies (Benhabib and Spiegel 1994, Griffith, Redding, and Van Reenen 2000). More recently, Lutz et al. (2008) confirmed that human capital accelerates the convergence towards the technological frontier, represented by the richest country. We integrate this idea into our model (model version 2, see table 4) by assuming that the absorptive capacity improves not only by the energy knowledge stock, but also by building up human capital (see equation A13 in the Appendix). In the second model variant (model version 3, see table 4), human capital is an essential input in the creation of both stocks of generic and energy knowledge (see eq. A14).

Model calibration

Education and R&D investments have been calibrated using the historical regional shares of expenditure over Gross Domestic Product for each region of the model. World expenditure on generic R&D in 2005 is 2.17% of GWP, global education expenditure 4.34%. As shown in Table 1, OECD countries have the largest share in both education and R&D expenditure.

Table 1. R&D investments and education expenditure. Historical data at the calibration point of 2005 (% GDP)

Historical data - 2005	Energy R&D (IEA)	Generic R&D (WDI)	Education (WDI)
WORLD	0.03%	2.17%	4.34%
OECD	0.03%	2.49%	4.55%
NON-OECD	n.a.	0.93%	3.62%

IEA: International Energy Agency
WDI: World Development Indicators

[3] Although it would be natural to characterise spillovers in the general purpose R&D sector, we refrain from doing so, mostly because of consistency with the empirical study that is used to calibrate our model, which did not account for spillovers. In addition, previous studies (see Bosetti et al 2008) show that the contribution of knowledge spillovers is limited.

The three factors of production, labour, energy and capital, are modelled as gross complements because most econometric studies suggest that this in fact reflect the historical patterns observed in the data. Carraro and De Cian (2009), using yearly data, estimated the elasticity of substitution between capital, labour and energy equal to 0.3. However, in the model, a higher value equal of 0.7 is chosen for two reasons. First, the model time step is of five years whereas the estimated value is based on yearly panel. The elasticity of substitution over five years is higher than the elasticity over one year, as discussed in Pessoa et al. (2005). Second, the value 0.3 is based on the evidence from developed economies. In contrast, developing countries are characterised by higher economic growth and larger substitution possibilities. Because we do not have the data to differentiate developed and developing countries, we have chosen a common value that made it possible to replicate regional economic growth patterns as in Bosetti et al. (2009). It is important to mention that the estimated elasticities vary quite significantly from very low to high values even greater than one (see for example van der Werf , 2008). The key driver for the direction of technical change is whether the elasticity is greater or smaller than one, but the actual value does not affect the direction of the results. Table 2 summarises the values of key parameters.

Table 2. Substitution elasticity between labour, capital, and energy (σ) and factor elasticity with respect to endogenous technology drivers

σ	0.7
χ_L *(HK)*	0.17
χ_{EN} *(R&D)*	0.60
χ_K *(R&D)*	0.26

A substitution elasticity less than one implies that inputs can be substituted with each other, but with some rigidity. When an input becomes more productive and there is full employment of resources, additional productivity leads to additional output. This scale effect puts an upward pressure on the demand for other inputs as well, and thus on energy. As a consequence, assuming there are no changes in the energy mix, energy-related emissions would increase. This argument neglects the distinction between skilled and unskilled labour, which would make the discussion more complicated. A relationship of complementarity between labour and other inputs (capital) is typically found when skilled labour is considered. Instead, empirical studies found that capital tend to be a substitute for unskilled labour. As a consequence, the stock of human capital drives a form of technical progress that is energy-using. In contrast, the net effect of generic innovation is energy-saving if it improves energy productivity more than capital.

Regarding the calibration of indirect effects we made the following assumptions. In the first variant (model 2), human capital is simply added to the energy knowledge stock in the absorptive capacity component of equation A13. The calibration of the indirect contribution of human capital to knowledge formation (model 3) is less straightforward due to the lack of clear empirical guidance. A few studies tested the hypothesis that innovation is influenced by the endowment of human capital by estimating a Cobb-Douglas production function in which total factor productivity is determined by R&D, human capital, and their interaction. Both Griffith, Redding, and Van Reenen (2000), using a panel of OECD countries, and Teixeira and Fortuna (2004), using times series for Portugal, found a positive and significant coefficient associated with the interacting term, indicating a positive relationship between innovation and human capital. For the contribution of human capital to knowledge creation (γ^{EDU}) we choose a range of values between 0.1 and 0.4.[4] The maximum value experimented corresponds to the coefficients estimated by Griffith, Redding, and Van Reenen (2000) and Teixeira and Fortuna (2004), which are close to 0.4. It should be pointed out that these empirical studies consider the joint effect of human capital and innovation on total factor productivity growth. This approach is different from estimating a direct relationship between human capital and innovation using an innovation production frontier, which instead is the modelling approach adopted in this paper.

Model testing

Before considering the implications of climate policy, we perform an ad-hoc experiment to test the macroeconomic effects of increasing education expenditure. We impose a 10% exogenous increase in education expenditure and we compute the elasticity of selected variables. For this testing exercise, we use the first model version (with no indirect effects). As reported in Table 3, the elasticity of final output to education ($\frac{\Delta Y}{\Delta I_{EDU}}$) is larger than zero, indicating a positive relationship between education expenditure and output growth. This result occurs when education is financed with consumption taxes (Blankenau and Simpson 2003). In the WITCH model education expenditure is financed out of the budget constraint and there are no distorting taxes on labour or capital. Additional education expenditure comes at the costs of lower consumption, but only in the short-term. After 2035, the growth effect increases consumption possibilities as well, as indicated by the positive value of the elasticity.

[4] It is reasonable to expect the education effect on knowledge to be lower than the effect of both R&D investments and capital stock. The size of this parameter is also constrained by the value of the other parameters and the restriction that the sum cannot exceed 1. Parameters in the innovation production frontier have been recalibrated so as to yield the same baseline as in the basic model.

The expansion of economic activity has two additional effects. Emissions increase because economic growth puts an upward pressure on energy demand. At the same time, economic growth increases the amount of resources available for all forms of innovation, pointing at the complementarity between knowledge and human capital. Both generic and dedicated energy R&D increase, although the effect on generic innovation is slightly larger. Because part of innovation is energy-saving, in the medium/long-term this leads to a peak and decline (after 2050) of the elasticity of emission to education, whereas the elasticities of output and consumption continue to increase over time.

Table 3. Elasticities to education expenditure when this is increased as by 10%

	$\frac{\Delta Y}{\Delta I_{EDU}}$	$\frac{\Delta C}{\Delta I_{EDU}}$	$\frac{\Delta EMI}{\Delta I_{EDU}}$	$\frac{\Delta I_{R\&D}}{\Delta I_{EDU}}$	$\frac{\Delta I_{R\&De,j}}{\Delta I_{EDU}}$	ΔI_{EDU}
2015	0.025	-0.040	0.019	0.026	0.020	10%
2030	0.057	-0.006	0.045	0.063	0.054	10%
2050	0.082	0.023	0.060	0.090	0.079	10%
2100	0.102	0.057	0.054	0.103	0.090	10%

This simple exercise illustrates how investing in human capital formation affects not only economic growth and consumption, but also innovation and emissions. In light of these results, what is the expected outcome of climate policy? On the one hand, human capital is pollution-using and therefore it may make the achievement of a stabilisation target more difficult. On the other hand, the positive effect education has economic growth and innovation may partially compensate the economic loss due to climate policy. These issues are explored in the next Section.

3. Implication of stand-alone climate policies

We now turn to the implications of a climate policy on the accumulation of knowledge, human capital, and ultimately the direction of technical change. Table 4 summarises the differences across the three specifications of endogenous technical change considered.

Table 4. The role of human capital in the three model versions considered

	Human capital enhances labour productivity	Human capital enhances absorptive capacity	Human capital enters as input in the innovation production function
Model 1	Yes	No	No
Model 2	Yes	Yes	No
Model 3	Yes	No	Yes

3.1 Climate policy when human capital has a direct effect on labour productivity (model 1)

We consider a climate policy in which all regions cooperate on the stabilisation of GHG concentrations at 550 CO2-eq by 2100[5], which defines the global cap on emissions. An international cap-and-trade system allows regions to buy and sell permits on the world market so as to achieve the target in the most cost-effective way, equalising marginal costs of abatement across regions[6]. The setting is that of cost-effectiveness and therefore the macroeconomic costs of the policy do not consider the benefits due to reduced climate change damages.

When facing a climate policy constraint, each region reshapes the optimal mix of investments to meet the constraint at the minimum cost. The carbon price signal reallocates resources towards low carbon technologies (renewable energy, coal equipped with carbon capture and storage, and nuclear), energy efficiency R&D, clean energy R&D, and subsequently to the deployment of the technologies (breakthrough are clean technologies that replace fossil fuels). In the model, the cost of breakthroughs is endogenously driven by R&D in the first place and, once the technology is deployed, by installed capacity following a two-factor learning curve (see eq. A11).

Figure 1 shows that climate policy stimulates dedicated investments in energy as well as general purpose innovation. This is due to the fact that general purpose R&D, by raising the productivity of

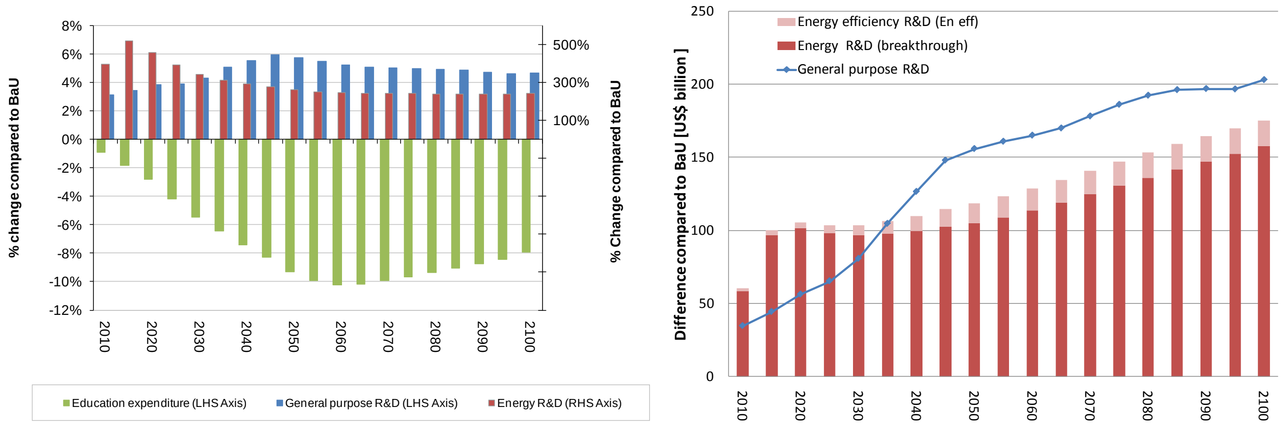
[5] It should be stressed that the chosen climate policy scenario is only illustrative. The goal of this paper is to understand the basic mechanisms behind induced innovation when there is also human capital. We therefore abstract from second-best considerations and from the analysis of more realistic policy scenarios.

[6] Permits are allocated on an equal per capita basis. This allocation schemes tend to favour developing countries. However, the goal is not to provide a comprehensive evaluation of different policy architectures, but rather to emphasise the trade-off and/or the synergies between different policy goals at the global level.

energy more than that of capital, improves energy efficiency, and this is a cost-effective abatement option. Figure 1 also shows the allocation of energy R&D between energy efficiency measures and breakthrough. Energy innovation is mostly directed at reducing the costs of breakthrough technologies because this will reduce the long-run costs of decarbonising the energy system. In absolute levels and over the whole century, climate policy allocates a comparable amount of resources to energy and general purpose R&D. There is, though, a difference in the time profile. Energy R&D increases mostly in the short-run, as a response to the anticipation of a rising carbon price. General purpose R&D instead overtakes energy R&D after 2040.

Both forms of innovation reduce the energy per unit of output, and therefore are complements rather than substitutes. This result differs from previous findings that considered different R&D programs, but neglected the role of human capital (Goulder and Schneider 1999, Sue Wing 2008, Carraro, Massetti and Nicita 2009, Massetti and Nicita 2010). For example, Carraro, Massetti and Nicita (2009) and Massetti and Nicita (2010), assume that non-energy R&D is energy-using. Therefore, climate policy increase energy R&D, but reduces non-energy R&D. Our result is in line with recent empirical evidence, which confirmed that crowding-out between clean and dirty energy R&D might exist, but not between innovation in the energy and non-energy sector (Popp and Newell, 2009).

Figure 1. Additional investments in various types of knowledge in the climate policy with respect to the Business as Usual (BaU)



Regarding the results on human capital, Figure 1 shows that climate policy induces a crowding-out on education expenditure. In absolute numbers the resources that are diverted away from the education sector are significant, reaching about 1 trillion USD after 2050. As already anticipated, this is due to the fact that human capital is labour-augmenting and to the complementarity between energy and labour. This is a result that has been already found in the literature on environmental policy and human capital. When pollution is linked to final output, environmental policy can reduce education expenditure and slow down human capital accumulation (Gradus and Smulders 1993, Hettich 1998, Pautrel 1998).

3.2 Climate policy when human capital has an indirect effect on absorptive capacity (model 2)

We now turn to the effect of climate policy when human capital has an indirect effect on the capacity to absorb foreign knowledge. Our model features international spillovers of energy knowledge. Foreign energy knowledge can contribute to the creation of a domestic stock of energy knowledge, provided the absorptive capacity is sufficiently large and depending on the distance from the technology frontier, defined as the stock of energy knowledge in high-income countries[7] (Bosetti et. al 2008). Investing in energy R&D is an important mitigation because it increases energy efficiency measures and favours the large scale deployment of zero-carbon technologies. The knowledge stock can be enhanced by either investing domestically in energy R&D or by using the ideas and notions already developed in other countries. However, this latter option is effective only if countries have the minimum capacity required to exploit other regions' ideas. We upgrade this feature by assuming that human capital can contribute to improve one country absorptive capacity, which in the original model depends only on the energy knowledge stock (see equation A13 in the Appendix). Human capital, being an input in the creation of new energy knowledge, has an indirect energy-saving effect, though of a small magnitude compared to the more direct effect on labour productivity.

Our results indicate that adding human capital as a determinant of absorptive capacity does not significantly affect the dynamics of innovation and education expenditure (see Table 5). Under this model specification, climate policy induces a slightly reduced crowding-out, at most 12% smaller than in the basic model (1). Energy R&D investments are also lower, especially during the first decades, because human capital increases the capacity to benefit from the pool of international energy knowledge, thus reducing the requirement in terms of domestic investments. Medium- and long-term investments in generic R&D slightly increase, driven by the positive scale effect on economic growth. The macroeconomic costs of the climate policy are reduced from 1.37% to 1.32% of net present value consumption.

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[7] High income countries in the WITCH model are United States, Western Europe, Eastern Europe, South Korea, Australia, Canada, Japan, New Zealand.

Table 5: Human capital and knowledge investments in the climate policy.
Change between model 2 and model 1 in relative and absolute terms (2005USD Billion in parenthesis)

	Energy R&D	General purpose R&D	Education expenditure
2015	-27.46% (-23.02)	-0.53 (-7.48)	1.25% (36.93)
2030	-19.88% (-14.86)	0.00% (0.00)	1.48% (71.29)
2050	-16.39% (-9.49)	0.698% (20.00)	1.28% (101.72)

This exercise indicates that –according to our model specification- the indirect effect of human capital on the capacity to absorb foreign knowledge in the clean energy sector can only partly reduce the contraction of education expenditures. The limited role of energy R&D spillovers is in line with what originally found by Bosetti et. al. (2008), confirmed a robustness analysis of the parameter space by means of sensitivity analysis.

3.3 Climate policy when human capital has an indirect effect on knowledge creation (Model 3)

The results regarding the crowding out of climate policy on human capital also follow from the assumption that human capital does not affect the process of creation of new ideas and technological innovations. To incorporate this mechanism into our framework, we introduce model 3 where the innovation frontier of both energy and generic R&D is also linked to the stock of human capital (see equation A14 in the Appendix). Through this additional channel, human capital has an indirect impact on energy and capital productivity. Due to the lack of clear empirical guidance, we perform sensitivity analyses over a wide range of elasticities between human capital and knowledge (between 0.1 and 0.4).[8] This channel of interaction is additional to the one discussed in the previous section.

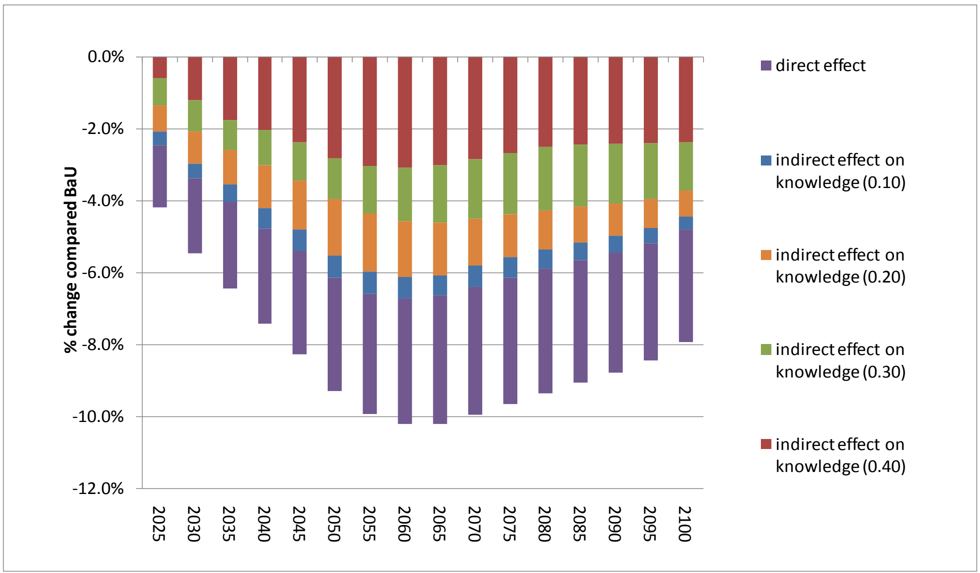
Figure 2 shows the results from this formulation. Because of the additional link between human capital and knowledge, education becomes an essential input in the production of knowledge, which has an energy-saving net effect, as discussed in Section 2.1. For this specification, even with a small elasticity, the crowding-out of education expenditures is

[8] It is reasonable to expect the education effect on knowledge to be lower than the effect of both R&D investments and capital stock. The size of this parameter is also constrained by the value of the other parameters and the restriction that the sum cannot exceed 1. Parameters in the innovation production frontier have been recalibrated so as to yield the same baseline as in the basic model.

significantly mitigated. This effect is more pronounced than the absorptive capacity one described in the previous paragraph, essentially because of the model formulation. Human capital receives a share of 0.1 in the knowledge creation process. Although international knowledge gets a slightly larger share equal to 0.15, the stock of foreign energy knowledge is much smaller and in addition only part of that is used by the recipient country. Further increasing the contribution of human capital (e.g. increasing the elasticity) continues to reduce the crowding-out, although by a smaller margin. However, the sign of the relation between climate policy and education is never reverted for the various parameterisation considered, and education is always crowded out.

Regarding innovation, investments in generic R&D are initially reduced compared to the basic model in which knowledge grows only with existing knowledge stock, but after 2040-2050 they become larger. However, the magnitude of variation is small, at most 1.16% in 2100. In contrast, energy R&D investments are reduced more significantly, especially during the first decades. Less dedicated innovation is needed to meet the stabilisation target because the stock of human capital adds a notable contribution to develop the energy knowledge stock that drives energy efficiency improvements and reduces the cost of advanced carbon-free technologies. The macroeconomic costs of the climate policy are reduced from 1.37% to 0.92% of net present value consumption when the share on human capital in knowledge production is 0.1. Consumption losses fall further to 0.66% when this share is increased to 0.4.

Figure 2. Education expenditure in the climate policy (changes with respect to BAU) under model 1 and three parameterisation of model 3 (γ^{EDU}=*0.1,0.2,0.3,0.4*) .



3.4 Sum up of the implications of climate policy under different model specifications

The analysis carried out with the three model variants described in the previous Sections points to similar conclusions. Climate policy increases innovation, both in terms of generic and energy R&D, but crowds out part of the investments in education. Although modelling the indirect effects of human capital on absorption capacity and knowledge formation is able to lessen the crowding-out induced by climate policy, the direct, energy-using effect is shown to prevail. A summary of these results is provided in Table 6.

It should be stressed that modelling results ultimately depend on the estimated elasticities reported in Table 2, which are the central value estimates. The confidence intervals of those estimates are very broad. This implies that there are combinations of the three elasticities for which the indirect effects of human capital can offset the crowding-out induced by climate policy. This can occur for example when the elasticity of labour productivity to human capital is set equal to the lower bound of the confidence interval (0.02), while the other two parameters are left equal to the central value estimates. In this case, the indirect effect on absorptive capacity and knowledge formation (assuming a contribution equal to 0.1) prevails.

Table 6: Impact of climate policy on innovation and human capital dynamics: summary across model specifications. Percentage change of cumulative investments compared to BaU (2005USD Trillion in parenthesis)

	Basic model (model 1)	Basic model+ indirect effect on absorptive capacity (model 2)	Basic model+ indirect effect on knowledge creation (model 3)
Energy R&D	268% (12.1)	228% (10.4)	249% (9.2)
General purpose R&D	4.9% (13.4)	5.0% (13.9)	5.6% (12.8)
Education expenditure	-8.4% (-76.7)	-8.0% (-74.3)	-5.3% (-54.3)
Policy Costs (Discounted Consumption loss)	-1.37%	-1.32%	-0.92%

The general results point to a potential conflict between policies to attain climate stabilisation and human capital improvements. This implies that the human capital crowding-out needs to be addressed by specific policies. In the next Section we evaluate a combination of climate and education policy.

4. Coupling climate and education policies

Climate policy targets are likely to be additional to other policy commitments. An example is given by the EU active role in climate policy as well as its commitment to sustaining education and innovation. Another example is provided by the Millennium Development Goals (MDGs), which are eight different objectives that have been accepted by 189 countries and that should be achieved by 2015. Universal primary education and sustainable development, which includes climate change mitigation, are two of the eight Goals. The Fourth Assessment Report (IPCC, 2007) also emphasised that, to be effective, climate policy should be supplemented by generic socio-economic development and increased mitigative capacity. This suggests that enhancing education, a determinant of mitigative capacity (Yohe, 2001), is a policy objective itself. Primary education is almost universal in all developed countries and many developing countries are on the right track to achieve the Millennium Development Goals (*on-track* countries). Achieving universal primary education is particularly challenging in poor countries such as South Asia (SASIA) and Sub-Saharan Africa (SSA).

Against this background, we analyse a combination of climate and education policy. We design the following education policy. The Sub-Saharan Africa and South Asia (SSA and SASIA) regions will increase education investments so that the fraction of population currently *off-track* will be *on-track* from 2015 onwards[9]. The remaining regions will maintain the path of education expenditure foreseen in the no-climate policy case, as current spending is already consistent with the achievement of the MDG. In order to compute the additional spending on education in SSA and SASIA we combined the percentage of population *off-track*[10] from Glewwe et al. (2006) with population projections form the WITCH model. We also used the estimates of average spending per student provided by Glewwe et al. (2006), which amounts to US$ 46 Billion in SASIA and US$ 68 Billion in SSA. Between 2010 and 2015, Sub-Saharan Africa and South Asia increase education expenditure by US$ 100 Billion a year, which is comparable to current spending on

[9] Countries or population are classified *on-track* in achieving universal primary education if continuing on linear trends between 1990 and 2002 will result in a completion rate above 95% by 2015. *Off- track* means that the completion rate is projected to be below 50% in 2015 (seriously off track) or below 95% (moderately off track).

[10] The implicit assumption is that average spending and the percentage of population *off-track* remains constant between 2000 and 2015.

Official Development Assistance[11]. The macroeconomic effects of combining education and climate policy are shown in Table 7.

Table 7 Global macroeconomic effects of joint climate and education policies. Basic model with only direct effect (model 1). Percent changes compared to BaU, 5% discounting for NPV.

	Education expenditure	**Generic R&D**	**Energy R&D**	**Output**	**Consumption**
2030	0.81%	4.82%	341.23%	-1.03%	-1.13%
2050	0.02%	6.39%	260.48%	-2.09%	-1.88%
2100	0.00%	5.68%	242.61%	-1.37%	-1.41%
NPV	*1.13%*	*4.60%*	*316.14%*	*-1.03%*	*-1.12%*
NPV (Climate policy only)	*-5.31%*	*4.15%*	*317.97%*	*-1.37%*	*-1.09%*

Adding the education policy stimulates further innovation, especially generic R&D, which has a direct impact on factor productivities and thus on economic growth. The increase in education expenditure also puts an upward pressure on emissions as well. This result is in part due to the elasticities of output and emissions to education investments, shown in Table 3. The elasticity of output is larger than that of emissions and therefore the additional effort required to comply with the target is limited. This is confirmed by the almost negligible impact on the marginal abatement costs. The carbon price increases, but only slightly (at most by 2% at the end of the century) and the effect on output growth partially compensates the costs of climate policy.

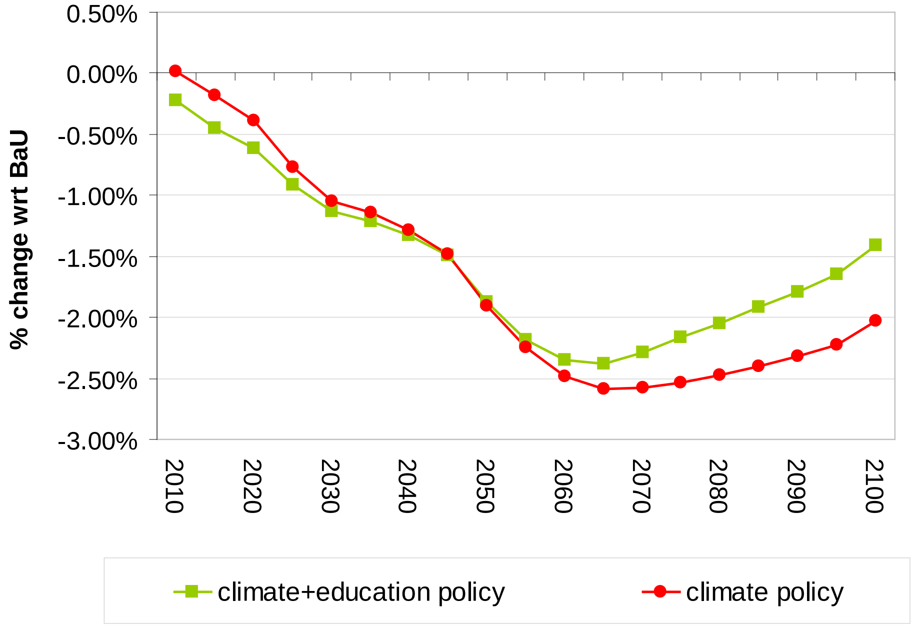
In Net Present Value, climate mitigation costs are lower in terms of gross world output, but higher in terms of consumption. This result raises the issue of the appropriate metric to measure the costs of a policy (Hourcade and Ghersi, 2008). Whereas output provides a measure of the macroeconomic effects, consumption is a better indicator of welfare.

In addition, net present values are aggregate figures that hide a trade-off between short-term and long-term consumption, which is further analysed in Figure 3. In the short-term, education policy absorbs additional resources, reducing consumption possibilities. However, short-term, additional education expenditure pays off in the long-term, when it increases overall economic growth, and ultimately consumption.

From this experiment of combined policies we can conclude that the crowding-out effect that climate policy tends to have on education can be corrected at moderate and temporary welfare costs. That is, adding a policy goal targeted at education does not jeopardise the achievement of the other objective, that of stabilising GHG concentrations in the atmosphere.

[11] After 2015 SSA and SASIA continue to spend at least the average amount required to have all population *on-track*.

Figure 3. Consumption path in two policy scenarios (basic model with only direct effect). Percent changes compared to BaU.



5. Conclusions

This paper has explored the relationship between innovation, human capital, and climate policy by means of an Integrated Assessment Model. This approach is meant to advance the current status of climate change economics research and to clarify some of the connections between climate change and economic development. To our knowledge, this is a first of its kind modelling assessment of the interplay between two important determinants of economic growth, innovation and human capital, in the context of climate policy.

First, we proposed a production structure with endogenous technical change supported by and calibrated on the empirical evidence that points at a direct relationship between human capital and labour productivity. Using this basic structure, we analysed the indirect effect of human capital on technological absorption and explored the relationship between human capital and innovation. Using these alternative formulations, we analyse how climate policy affects innovation and the accumulation of human capital.

Results indicate that climate policy stimulates investments in energy R&D without reducing those in generic R&D if there are complementarities between the these two forms of investments. Although generic R&D has a pollution-using effect through capital productivity, it also has an energy saving effect

When only the direct effect of human capital is considered, advancements in labour productivity have a negative impact on the environment because labour and energy are gross complements. Therefore, climate policy decreases education investments (by at most 10%). This is due to the capital-skill complementarity assumption embedded in our production structure.

Modelling the indirect effect of human capital on absorptive capacity mitigates the crowding-out effect of climate policy only slightly. In this case, human capital augments the ability to absorb foreign knowledge that can be applied to improve energy efficiency or to reduce the price of advanced, zero-carbon technologies. However, the indirect effect is not able to counterbalance the direct impact on labour productivity.

All in all, the energy-using, direct effect of human capital always prevails and therefore the crowding-out induced by climate policy needs to be addressed by a specific policy. Inspection of a policy mix that combines climate and education targets shows that the crowding-out on education can be eliminated by incurring in small additional economic penalties, and only in the short-run. Increased human capital stimulates long-run economic growth, which ultimately reduces climate change policy costs. This result has important policy implications considering the growing concern that effective climate policy is conditional on solid economic development and therefore it needs to be supplemented by other policy targets.

An exploratory investigation of the interdependence between R&D and human capital shows that the crowding-out effect induced by the climate policy is lessened by a larger extent when education contributes to knowledge production. This exercise is a preliminary analysis meant to suggest the importance of additional empirical work in this area.

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Appendix: equations and variables

WITCH is a dynamic optimal growth model ("top-down") with a "bottom-up" representation of the energy sector. It can be classified as a hybrid model. The geographical coverage is global and world regions are grouped into twelve macro-regions sharing economic, geographic, and energy similarities. These regions are USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJANZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean).

The WITCH model includes a range of technology options that describe the use of energy and power generation. Different fuels can be used for electricity generation and final consumption: coal, oil, gas, uranium, and biofuels. Electricity can be generated using either traditional fossil-fuel-based technologies or carbon-free options. Fossil-fuel-based technologies include natural gas combined cycle (NGCC), oil, and pulverised coal (PC) power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with carbon capture and sequestration (IGCC+CCS). Carbon free technologies include hydroelectric and nuclear power, wind turbines and photovoltaic panels (Wind&Solar), and a backstop technology. A second backstop option represents an alternative to oil in transportation, such as hydrogen or second generation biofuels. The model features endogenous technical change in the energy sector in the form of both Learning-By-Researching and Learning-By-Doing

The model features a game-theoretic set-up that makes it possible to capture the non-cooperative nature of international relationships. Climate change is the major global externality, but other economic externalities induce free-riding behaviours and strategic interactions. The model can produce two different solutions. The cooperative solution is globally optimal because it maximises global social welfare and it internalises environmental and economic externalities. It represents a first-best optimum. The decentralised, or non-cooperative solution is strategically optimal for each given region (Nash equilibrium), but it does not internalise externalities. It represents a second-best optimum. An intermediate solution that internalises only the environmental externality can also be computed. The Nash equilibrium is computed as an open-loop Nash equilibrium. It is the outcome of a non-cooperative, simultaneous, open membership game with full information. This remaining of the Appendix describes the main equations of the economic module of the model. The complete description of all model equations can be found in Bosetti et al. (2007) and Bosetti et al. (2009).

In each region, indexed by *n*, a social planner maximises the following welfare function:

$$W(n) = \sum_t L(n,t)\{\log[c(n,t)]\}R(t) \quad \text{(A1)}$$

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

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

where $\rho(v)$ is the pure rate of time preference and $c(n,t) = \frac{C(n,t)}{L(n,t)}$ is per capita consumption. The budget constraint defines consumption as output less investments and operation and maintenance costs in different energy technologies *j, (Ij*) and *(O&M$_j$*) investments in final good *(I_c),* education expenditure *(I_{EDU}),* and investments in generic and energy R&D ($I_{R\&D}$, $I_{ER\&D}$,):

$$C(n,t) = Y(n,t) - \sum_i I_i(n,t) - \sum_j O\&M_j(n,t) - I_C(n,t) - I_{EDU}(n,t)$$
$$- I_{R\&D}(n,t) - I_{ER\&D}(n,t) - I_{BR\&D}(n,t) \quad \text{(A3)}$$

Output is produced via a nested CES function that combines capital, labour, and energy services:

$$Y(n,t) = H(n,t)\Omega(A_K(n,t)K(n,t)^{\rho Y} + A_L(n,t)L(n,t)^{\rho Y} + A_{EN}(n,t)EN(n,t)^{\rho Y})^{\frac{1}{\rho Y}} \quad \text{(A4)}$$

Neutral technical change (*H)* evolves exogenously with time. Factor productivity is endogenous and depends on the stock of generic knowledge (*R&D)*, or human capital (*HK)*. Energy productivity is also affected by a dedicated stock of energy knowledge (*R&D$_E$)*:

$$AK(n,t) = AK0(n,t)\left(\frac{R\&D(n,t)}{R\&D(n,0)}\right)^{\chi_K}$$
$$AE(n,t) = AE0(n,t)\left(\frac{R\&D(n,t) + R\&D_E(n,t)}{R\&D(n,0) + R\&D_E(n,0}\right)^{\chi_E} \quad \text{(A5)}$$
$$AL(n,t) = AL0(n,t)\left(\frac{HK(n,t)}{HK(n,0)}\right)^{\chi_L}$$

The production of both human capital and knowledge is characterised by intertemporal spillovers, as the stock available in the economy at each point in time contributes to the creation of the future stock. The new addition to human capital (Z_{EDU}) is produced using a Cobb-Douglas combination of the existing stock of human capital (*HK)* and the current expenditure in education (I_{EDU}). In a similar way, the available knowledge stock (*R&D*) and current R&D investments ($I_{R\&D}$) are combined to produce the new knowledge capital ($Z_{R\&D}$). The sum of the exponents is less than one to account for diminishing returns on education and R&D:

$$
\begin{aligned}
&Z_{EDU}(n,t) = \alpha_{EDU} I_{EDU}{}^{\beta_{EDU}} HK^{\varphi_{EDU}} \\
&Z_{R\&D}(n,t) = \alpha_{R\&D} I_{R\&D}{}^{\beta_{R\&D}} R\&D^{\varphi_{R\&D}} \\
&\text{where} \\
&\beta_{EDU} + \varphi_{EDU} < 1 \\
&\beta_{R\&D} + \varphi_{R\&D} < 1
\end{aligned}
\tag{A6}
$$

The stock of both knowledge and human capital depreciate over time. Following Jorgenson and Fraumeni (1992), the depreciation rate of human capital (δ_{EDU}) is lower than the depreciation rate of knowledge ($\delta_{R\&D}$) (2% and 5% per year respectively). The final laws of accumulation read as follows:

$$HK(n,t+1) = HK(n,t)(1-\delta_{EDU}) + Z_{EDU}(n,t)$$

$$R\&D\ (n,t+1) = R\&D(n,t)(1-\delta_{R\&D}) + Z_{R\&D}(n,t)$$

(A7)

Investments in R&D that build up the stock in equation (A6) represent the total innovative activity of the economy. Therefore, we also refer to it as generic innovation. Investments in energy R&D ($I_{e,j}$) are combined with the existing stock of knowledge ($R\&D_{e,j}$) and the knowledge of other countries (*SPILL*) to produce new dedicated energy knowledge ($Z_{e,j}$). The model specifies three different energy knowledge stocks, energy efficiency and two stocks of breakthrough knowledge, which are denoted with the index *j=en eff, breakthrough.*

$$Z_{e,j}(n,t) = \alpha_{e,j} I_{R\&DE,j}{}^{\beta_{e,j}} R\&D_{e,j}{}^{\varphi_{e,j}} SPILL_{e,j}(n,t)^{d}$$

where (A8)

$$\beta_{e,j} + \varphi_{e,j} + d < 1$$

with the standard accumulation equation:

$$R\&D_{e,j}(n,t+1) = R\&D_{e,j}(n,t)(1-\delta_{e,j}) + Z_{e,j}(n,t) \qquad \text{(A9)}$$

The contribution of foreign knowledge (SPILL) is not immediate but depends on the interaction between two terms (Bosetti et. al 2008): the first describes the absorptive capacity whereas the second captures the distance from the technology frontier, which is represented by the stock of knowledge in rich countries (USA, WEURO, EEURO, CAJANZ and KOSAU). Domestic investments are required in order to benefit from the international pool of knowledge

$$SPILL_{e,j}(n,t) = \frac{R\&D_{e,j}(n,t)}{\sum_{HI} R\&D_{e,j}(n,t)} \left(\sum_{HI} R\&D_{e,j}(n,t) - R\&D_{e,j}(n,t)\right) \qquad \text{(A10)}$$

The WITCH model includes two backstop technologies (*tec*). These are innovative, zero carbon technologies currently not commercialised because very expensive. They necessitate dedicated R&D investments to become economically competitive and deployment to become available on large scale. The costs of these technologies are modelled with a two-factor learning curve. The unit cost of each backstop technology(P_{tec}) evolves over time with technology deployment (CC_{tec}) and the accumulation of a dedicated knowledge stock ($R\&D_{tec}$):

$$\frac{P_{e,j}(n,t)}{P_{e,j}(0,t)} = \left(\frac{R\&D_{e,j}(n,t-2)}{R\&D_{e,j}(n,0)}\right)^{-c} * \left(\frac{CC_{e,j}(n,t)}{CC_{e,j}(0,t)}\right)^{-b} \qquad \text{(A11)}$$

where *j=breakthrough*. *R&D* stock accumulates with the perpetual rule and with the contribution of international knowledge spillovers as in eq. (A8-A9)

Equations (A1)-(A11) describe the basic formulation of the model. Starting from this version, we considered two possible variations. First (section 3.2), human capital has an indirect effect on technological absorption and it contributes to increasing the absorptive capacity in the energy sector:

$$SPILL_{e,j}(n,t) = \frac{\left(R\&D_{e,j}(n,t) + HK(n,t) \right)}{\sum_{HI} R\&D_{e,j}(n,t)} \left(\sum_{HI} R\&D_{e,j}(n,t) - R\&D_{e,j}(n,t)\right) \qquad \text{(A13)}$$

Second (section 3.3), human capital is an input in the creation of both stocks of generic and energy knowledge. Therefore, equations (A6), (A8), and (A12) are modified as follows

$$Z_{R\&D}(n,t) = \overline{\alpha}_{R\&D} I_{R\&D}(n,t)^{\beta_{R\&D}} R\&D(n,t)^{\overline{\varphi}_{R\&D}} HK(n,t)^{\gamma_{EDU}}$$

$$\text{(A14)}$$

$$Z_{e,j}(n,t) = \overline{\alpha}_{e,j} I_{e,j}(n,t)^{\beta_{e,j}} R\&D_{e,j}(n,t)^{\overline{\varphi}_{e,j}} SPILL_{e,j}(n,t)^{d} HK(n,t)^{\gamma_{EDU}}$$

When human capital is introduced in the production function of new ideas, the parameters α and φ , are recalibrated so that the dynamics of knowledge and education investments replicate those in the model version 1, $\overline{\alpha} < \alpha$ and $\overline{\varphi} < \varphi$.