Environ Model Assess (2014) 19:85–98
DOI 10.1007/s10666-013-9385-z

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

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Received: 30 August 2012 / Accepted: 24 September 2013 / Published online: 11 October 2013

Abstract This paper looks at the interplay between human capital and innovation when climate and educational policies are implemented. Following recent empirical studies, human capital and general purpose research and development (R&D) are introduced in an integrated assessment model used to study the dynamics of climate change mitigation. Our results suggest that climate policy stimulates general purpose as well as clean R&D but reduces the incentive to invest in human capital formation. Both innovation and human capital have a scale effect, which increases pollution, as well as a technique effect, which saves emissions for each unit of output produced. While the energy-saving effect prevails when innovation increases, human capital is pollution-using, also because of the gross complementarity between the labor and energy input. When the role of human capital is the key input in the production of general purpose and energy knowledge is accounted for, the crowding-out of education induced by climate policy is mitigated, though not completely offset. By contrast, a policy mix that combines educational as well as climate objectives offsets the human capital crowding-out, at moderate and short-term costs. Over the long run, the policy mix leads to global welfare gains.

Keywords Climate policy · Innovation · Human capital

JEL Classification O33 · O41 · Q43

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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 and a number of reviews have also been published on the topic (see among others [1–3]). 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 on the macroeconomic costs of climate policy. A first wave of studies focused on innovation in the energy sector, because of the relevance of energy efficiency measures and decarbonization of energy as mitigation strategies [4–6]. 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 [7, 8]). 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 research and development (R&D) sectors.

An increasing number of climate-economy models now feature both energy-saving and energy-using endogenous technical change [9–13]. 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 [9] and Otto et al. [10] emphasize how the general equilibrium effect, due to the policy-induced income reduction, can lower the overall amount of resources available for knowledge creation. Gerlagh [11] shows that if a sufficient amount of investments goes to energy-saving technical change, then there might be a research dividend and overall research activity may increase. Carraro et al. [12], and Massetti and Nicita [13] highlight that the complementarity between energy and non-energy inputs drives the direction of induced technical change, in line with the theory of directed technical change [14].

Guided by the empirical evidence on induced innovation [5, 15–17] and following mainstream growth theory (e.g., [14, 18–22]), most climate-economy models assume that the engine of technical change is the accumulation of knowledge or experience. Other drivers such as human capital [23, 24] or trade [7, 8, 25] have been neglected. The narrow focus on energy R&D has bounded the applicability of Integrated Assessment Model (IAM) to the study of clean innovation in relation to climate change. By omitting other engines of macroeconomic growth, the connections with economic developments have not been fully analyzed by the modeling literature. This paper explores this linkage and provides 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. Although the estimation of a macroeconomic relationship between human capital and economic growth has been problematic, especially because of data quality issues [26, 27], recent estimates [28, 29] suggest a positive relationship between human capital and economic growth. We name the effect of human capital on economic growth direct effect. By stimulating labor productivity, human capital increases the amount of resources available for productive usages, including innovation and education. This scale effect could have two implications. On the one hand, mitigation policy costs could increase, because of the greater size of the economy. On the other hand, policy costs could fall, because of the induced innovation effect.

Indirectly, human capital can increase the effectiveness of mitigation policies [30]. Human capital is an essential input in the creation of knowledge and new products, including cleaner and energy-saving technologies. Some studies do support the existence of a positive relationship between innovation and human capital, but at the aggregate level [31, 32]. To our knowledge, there are no empirical studies that have looked at the relationship between knowledge and human capital in the context of climate-related innovation. However, it seems reasonable to postulate that, on the supply side, human capital increases the opportunities for cleaner innovation. Education can also have indirect effects on the demand side. By increasing the awareness of the climate change problem, education can modify behaviors of consumers and producers and technology choices [33]. Education can also influence voting preferences towards parties that advocate and support climate policy [34].

Human capital is positively related to the capability of adopting new technologies, both among producers and consumers. The idea goes back to the model of technology diffusion introduced by Nelson and Phelps [35]. 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 skilled labor. 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 [36] has been empirically supported by a number of studies [31, 37]. More recently, Lutz et al. [28] confirmed that human capital accelerates the convergence towards the technological frontier, represented by the richest country.

Because of these mechanisms, there can be synergies between educational and climate change policies. A number of theoretical papers have investigated the interaction between human capital, innovation and the environment, but not with a specific focus on climate change policies. The theoretical literature demonstrates that results are sensitive to the way human capital and education come into the model. Whether education is included in the utility function or treated as a production input affects the results [38]. Whatever is the source of pollution, either output or input such as physical capital, plays a major role and all studies confirmed that this assumption is pivotal to determine the direction of the relationship between environmental policy and human capital accumulation [39–41]. These studies share the assumptions that, first education (or human capital) is the clean input and that, second the substitution possibilities between clean and dirty are sufficiently large. In most cases, a Cobb–Douglas production function is assumed. In addition, pollution is linked to production or physical capital and the role of polluting inputs, such as energy, is not considered. Therefore, this literature did not consider that the degree of substitutability between energy and non-energy inputs is a major driver of the effect of environmental policy on technical change, and thus on human capital as well.

In this paper, we use a numerical calibrated IAM, WITCH [6, 42, 43], to qualify the considerations on the interaction between human capital, innovation and the environment with reference to the specific case of climate change policies and energy innovation. This paper mainly focuses on analyzing the induced effect of climate policy on human capital and knowledge formation, evaluating how different formulations of endogenous technical change affect policy costs, and studying the interaction between climate and education policy. IAM, including WITCH, have been designed to characterize the dynamics of the climate system, of the energy sector, and to integrate those with the socioeconomic dynamics. The complexities of these different subsystems and the way they interact with each other make it difficult to rely on stylized economic models. In this context, oversimplification can lead to distorted policy implications and lack of numerical realism (see [22] and the critical response that followed, by Hourcade et al. [44] and Pottier et al. [45]). WITCH has a sophisticated characterization of endogenous technical change, but confined to the energy sector. We amend the macroeconomic production function to account for the effect of general purpose R&D and human capital. This introduces a direct link between human capital and economic growth. We also look at the indirect effects human capital could have on technology absorption and innovation. Given the lack of empirical studies to substantiate the model formulation and parameterization, we explore the relationship between human capital and innovation with sensitivity analysis on functional forms and parameter values. We propose a comparative analysis of climate policy under three alternative model specifications. This approach enables us to evaluate how the induced-technical change hypothesis responds to different representations of technical change. To our knowledge, this is the first modeling assessment of the interplay between two important determinants of economic growth, innovation, and human capital, in the context of climate policy. It should also be noted that the goal of this paper is not to contribute to the literature on public economics and education economics but rather to the literature on climate-induced innovation and technical change.

Our results indicate that climate policy stimulates both dedicated investments in energy R&D and general-purpose innovation, being the net effect of the latter energy-saving. Education expenditure, and over time the accumulation of human capital, would be reduced if human capital is energy-using. In the model, education augments the productivity of labor, which is gross complement to energy. The crowding-out of climate policy on education expenditure is lessened if resources are allocated to education (that contributes to the creation of human capital which is valuable in the clean energy innovation sector). In other words, while the direct effect of human capital is energy-using, the indirect effects—facilitating clean technology diffusion and innovation—are energy-saving. While our analysis highlights the importance of the mechanisms in the contexts of IAMs, more research is needed to quantify the magnitude of direct and indirect effects. This would help to make IAMs more policy relevant.

We also find that policies aimed at promoting education stimulate both energy and general-purpose innovation. This implies that a policy mix that combines a climate stabilization target with an educational policy could reduce the long-run macroeconomic costs of climate policy. The additional costs of implementing the two policies are transitory and the long-run, induced scale effect partly mitigates climate change policy costs. The result is mostly due to the cost-minimization framework and the mismatch between innovation costs and benefits. While the latter occur in the short-term, innovation benefits materialize in the long-term.

The rest of the paper is organized 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 IAM. Policy scenarios are analyzed 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 among labor (L), capital (K), and energy (EN)[1]:

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

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).

The idea that factor productivities can have input-specific dynamics has a theoretical foundation in the work on directed technical change [14]. The hypothesis that factor productivities are influenced by different variables, such as imports, education, and knowledge stocks has been empirically substantiated by numerous studies. However, most of them highlight the relationship between trade-related variables [25, 46–50], knowledge [51–55], human capital and total factor productivity. They assume an equal effect across production factors. To our knowledge, only Carraro and De Cian [8] identify the differentiated effect of human capital and knowledge on capital, labor, and energy inputs. 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 [8], where capital and energy productivity depend on the stock of general purpose knowledge (R&D) while labor productivity depends on human capital (HK):

$$\begin{aligned} A_K &= A_{K0}\mathrm{R\&D}^{\chi_K} \\ A_{\mathrm{EN}} &= A_{\mathrm{EN}0}\mathrm{R\&D}^{\chi_{\mathrm{EN}}} \\ A_L &= A_{L0}\mathrm{HK}^{\chi_L} \end{aligned} \quad (2)$$

[1] The choice of a non-nested CES as opposed to a nested CES between a capital labor 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 labor, are gross complements to energy.

With gross complementarity between factors of production (σ<1) and positive elasticity of human capital on labor productivity, χ_L, human capital has an energy-using effect:

$$\frac{\partial\left(\frac{\text{EN}}{L}\right)}{\partial \text{HK}} = (1-\sigma)\chi_L\left(\frac{P_L}{P_{\text{EN}}}\right)^{\sigma}\left(\frac{A_{Lo}\text{HK}^{\chi_L}}{A_{\text{EN}}}\right)^{-\sigma} \qquad (3)$$

$$\left(\frac{A_{Lo}\text{HK}^{\chi_L-1}}{A_{\text{EN}}}\right) > 0 \text{ if } \sigma < 1 \text{ and } \chi_{\text{L}} > 0$$

where P_L and P_{EN} represent the price of labor and energy, respectively. 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 [8] find that that $\chi_K<\chi_{\text{EN}}$, 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

2.2.1 Model Enhancement

The WITCH model [6, 42, 43][2] provides a good characterization 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 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 that enhance energy efficiency and investments that facilitate the development and uptake of innovative low carbon technologies (breakthrough technologies).

We add to this set-up two dedicated endogenous sources of factor-augmenting technical change (Eq. 7). Capital and energy productivities depend on a generic knowledge stock (the stock of general purpose R&D expenditure), whereas labor productivity increases with human capital (the stock of education expenditure), see Eq. (8). On top of the effect of general purpose R&D, dedicated energy efficiency R&D can specifically address improvements in energy efficiency (Eq. 8) or develop breakthrough technologies by reducing their unit investment cost (Eq. 14).

All different sources of technical change—energy R&D, general purpose R&D, and human capital—are now endogenous and compete for the finite resources available for investments.

The production of both human capital and knowledge is characterized 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 [5, 24, 56–58], we assume that human capital is produced using a Cobb–Douglas combination of the existing stock of human capital and current expenditure in education (Eqs. 9 and 10). In a similar way, the available knowledge stock and current R&D investments are combined to produce new knowledge (Eqs. 11 and 12). The creation of energy knowledge is also influenced by international spillovers (see Eq. 13). Foreign knowledge can impact the domestic process of knowledge creation depending on a country's absorptive capacity and distance from the frontier [59].[3]

To shed light on the role of different modeling choices, we compare three different specifications of human capital effects, summarized in Table 1. Model 1 only considers the direct effect of human capital on labor productivity, following the specification estimated in Carraro and De Cian [8]. Model 2 adds to the direct effect an indirect contribution to the international diffusion of technologies. In this model version, human capital increases the absorptive capacity in the energy spillover equation (see Eqs. 13 and 15, which refer to models 1 and 2, respectively). Model 3 explores the relationship between human capital and innovation, adding to the direct effect an indirect contribution to generic and energy knowledge production in Eqs. 9 and 11. In this model variant, human capital is an essential input in the creation of general purpose and energy knowledge (see Eq. 16). Figure 1 gives a graphical representation of the way human capital enters into the models in the three different formulations. Note that in model 3 human capital indirectly affects input productivities (A_L, A_{EN}, and A_K) as well as the cost of energy breakthrough technologies (P_{BACK}).

2.2.2 Model Calibration

Education and R&D investments have been calibrated using the historical regional shares of expenditure over gross domestic product (GDP) for each region of the model. World expenditure on generic R&D in 2005 is 2.17 % of gross world product (GWP), global education expenditure 4.34 %. As

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

[3] Although it would be natural to characterize 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 [59]) show that the contribution of knowledge spillovers is limited.

Table 1 Human capital effects in the three model versions considered

	Direct effect (human capital enhances labor productivity)	Indirect effect (human capital enhances absorptive capacity of international energy spillovers)	Indirect effect (human capital is an input in the R&D production function)
Model 1	Yes	No	No
Model 2	Yes	Yes	No
Model 3	Yes	No	Yes

shown in Table 2, OECD countries have the largest share in both education and R&D expenditure.

The three factors of production, labor, energy and capital, are modeled as gross complements, because most econometric studies suggest that this in fact reflect the historical patterns observed in the data. Carraro and De Cian [8], using yearly data, estimated the elasticity of substitution between capital, labor 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 5 years, whereas the estimated value is based on yearly panel. The elasticity of substitution over 5 years is higher than the elasticity over 1 year, as discussed in Pessoa et al. [60]. Second, the value of 0.3 is based on the evidence from developed economies. By contrast, developing countries are characterized by higher economic growth and larger substitution possibilities. As we do not have the data to differentiate developed and developing countries, we have chosen a

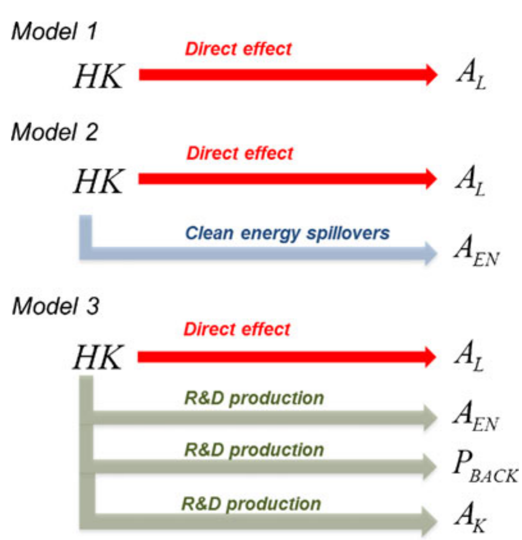

Fig. 1 Human capital effects in the three model versions considered. Graphical representation

common value that made it possible to replicate regional economic growth patterns as in Bosetti et al. [43]. It is important to mention that the estimated elasticities vary quite significantly from very low to high values even greater than one. 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 3 summarizes the values of key parameters.

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. Consequently, assuming there are no changes in the energy mix, energy-related emissions would increase. This argument neglects the distinction between skilled and unskilled labor, which would make the discussion more complicated. A relationship of complementarity between labor and other inputs (capital) is typically found when skilled labor is considered. Instead, empirical studies found that capital tend to be a substitute for unskilled labor. Consequently, the stock of human capital drives a form of technical progress that is energy-using. By contrast, the net effect of general-purpose 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 added to the energy knowledge stock in the absorptive capacity component of Eq. 15. 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. Griffith et al. [31]), using a panel of OECD countries, and Teixeira and Fortuna [32], 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 et al. [31] and Teixeira and Fortuna [32], which are close to 0.4. It should be pointed out that these empirical studies consider the joint effect of human capital and

[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.

Table 2 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

Table 4 Elasticities to education expenditure when this is increased by 10 %

	$\frac{\Delta Y}{\Delta I_{\text{EDU}}}$	$\frac{\Delta \text{Cons}}{\Delta I_{\text{EDU}}}$	$\frac{\Delta \text{EMI}}{\Delta I_{\text{EDU}}}$	$\frac{\Delta I_{\text{R\&D}}}{\Delta I_{\text{EDU}}}$	$\frac{\Delta I_{\text{R\&De, j}}}{\Delta I_{\text{EDU}}}$	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

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 modeling approach adopted in this paper.

2.2.3 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 (model 1, with no indirect effects). As reported in Table 4, the elasticity of final output to education ($\frac{\Delta Y}{\Delta I_{\text{EDU}}}$) is larger than zero, indicating a positive relationship between education expenditure and output growth. This result occurs when education is financed with consumption taxes [24]. In the WITCH model, education expenditure is financed out of the budget constraint and there are no distorting taxes on labor or capital. Additional education expenditure comes at the costs of lower consumption ($\frac{\Delta \text{Cons}}{\Delta I_{\text{EDU}}}$) 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.

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 general purpose and dedicated energy R&D increase, although the effect on general-purpose innovation is slightly larger. As part of innovation is energy-saving, in the medium to 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.

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 stabilization 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.

Table 3 Substitution elasticity between labor, 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

3 Implication of Stand-Alone Climate Policy

In this section, we examine the effect of climate policy on the dynamics of knowledge and human capital. In the climate policy, we considered all regions cooperate on the stabilization of greenhouse gas (GHG) concentrations at 550 CO_2-eq by 2100.[5] 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, equalizing 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,

[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 favor developing countries. However, the goal is not to provide a comprehensive evaluation of different policy architectures, but rather to emphasize the trade-off and/or the synergies between different policy goals at the global level.

and 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. 14). To highlight the effect of different representations of technical change dynamics, we present the results for the three models separately, starting with the model 1 in the next section.

3.1 Climate Policy When Human Capital Has a Direct Effect on Labor Productivity (Model 1)

In model 1, climate policy stimulates dedicated investments in energy as well as in general-purpose innovation (Fig. 2, right panel), being the net effect of the latter energy-saving (see Table 3). This result differs from previous findings with respect to models that considered different R&D programs but neglected the role of human capital [9, 12, 13]. For example, Carraro et al. [12] and Massetti and Nicita [13] assume that non-energy R&D is energy-using. Therefore, climate policy increases energy R&D, but reduces non-energy R&D. Our result is in line with a recent empirical study confirming that crowding-out is more likely between clean and dirty energy R&D rather than between energy and non-energy innovation [61].

Figure 2 (right panel) 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 decarbonizing 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.

Climate policy induces 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 labor-augmenting effect of human capital and the complementarity between energy and labor. This is a result that has been already expressed 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 [39, 40]. The next two sections show that the extent of the crowding-out depends on the representation of human capital's indirect effects.

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 in the clean energy sector. Foreign 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] [59]. In the model investing in energy R&D is an important mitigation option, because it increases energy efficiency measures and favors the uptake of zero-carbon technologies. The knowledge stock grows if countries invest domestically in energy R&D, but it is also influenced by the ideas and inventions developed in other countries (international spillovers of knowledge). International spillovers only have an impact if countries invest in R&D on their own, so as to develop a basic capacity to exploit other regions' ideas. Model 2 assumes that human capital adds to the role of energy R&D and enhances absorptive capacity, whereas in model 1 absorptive capacity only depends on the energy knowledge stock (see Eqs. 16 and 13 in the Appendix). In this way, human capital becomes an input in the creation of new energy knowledge and has an indirect energy-saving effect, though of a small magnitude compared with the more direct effect on labor productivity.

With this model specification, climate policy induces a slightly reduced crowding-out compared with what was found in model 1, at most 12 % less than in model 1 (see Table 5). Energy R&D investments are 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 general purpose 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 GDP.

3.3 Climate Policy When Human Capital Has an Indirect Effect on Knowledge Creation (Model 3)

We now consider the effect of climate policy when human capital is an explicit input in the creation of inventions, new ideas, and innovation. It means that countries can also decide to invest in education to increase the production of inventions. In model 3, human capital enters in the Cobb–Douglas that describes the innovation frontier of energy and general-purpose R&D (see Eq. A16 in the Appendix). Through this additional channel, human capital has an indirect impact on energy and capital productivity. Given the lack of clear empirical guidance, we perform sensitivity analyses over a wide

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

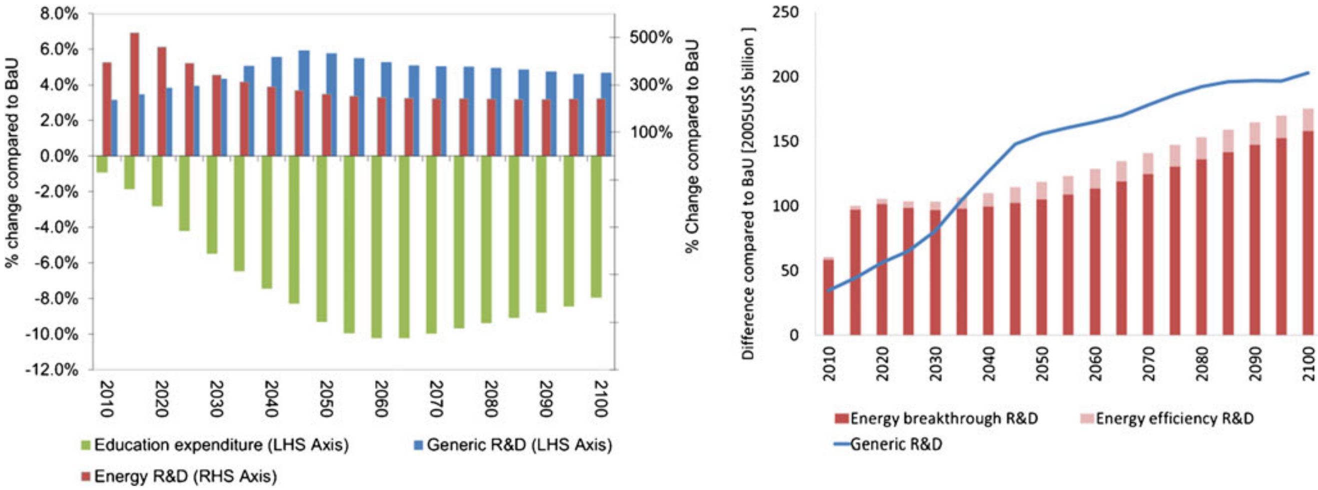

Fig. 2 Additional investments in general purpose knowledge, energy knowledge, and education induced by climate policy. Percentage change (*left*) and US$ billion difference (*right*) with respect to Business as Usual (*BaU*)

range of elasticities between human capital and knowledge (between 0.1 and 0.4).[8]

In model 3, even with a small elasticity, the crowding-out of education expenditures is significantly reduced (see Fig. 3). This effect is more pronounced than the absorptive capacity effect 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 of 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 parameterizations considered, and education is always crowded out.

Regarding innovation, investments in general-purpose R&D are initially reduced compared with 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. By contrast, energy R&D investments are reduced more significantly (compared with the basic model), especially during the first decades. Less dedicated innovation is needed to meet the stabilization 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. Compared with model 1 with no indirect effects, the macroeconomic costs of the climate policy are reduced from 1.37 % (in model 1) to 0.92 % (in model 3) of net present value GDP when the share on human capital in knowledge production is 0.1. GDP losses fall further to 0.45 % when this share is increased to 0.4.

By comparing the results of the three different models we can highlight the general results that hold across the different specifications and identify the modeling assumptions that mostly affect results. A summary of these results is provided in Table 6. Across all three model variants climate policy increases innovation, both in terms of general purpose and energy R&D, but it crowds out education expenditure. The magnitude of the reduction is mostly sensitive to assumption of human capital being an explicit input in the production of knowledge. This assumption also significantly affects policy costs, which are reduced significantly in model 3. Although modeling 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 always prevails.

It should be stressed that modeling results ultimately depend on the estimated elasticities reported in Table 3, which are the central value estimates. The confidence intervals of those estimates are very broad. This implies that there are

Table 5 Human capital and knowledge investments in the climate policy

	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)

Change between models 2 and 1 in relative and absolute terms (2005 US$ billion in parenthesis)

[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.

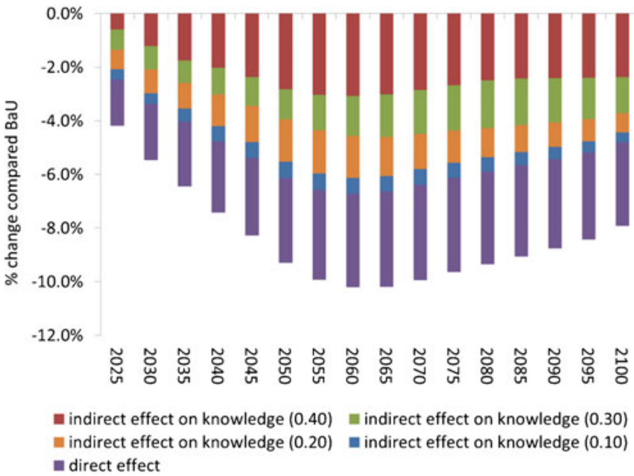

Fig. 3 Education expenditure in the climate policy (changes with respect to BAU) under model 1 and three parameterizations of model 3 (γ^{EDU}= 0.1, 0.2, 0.3, and 0.4)

Table 6 Impact of climate policy on knowledge and human capital dynamics

	Model 1 (direct effects)	Model 2 (direct+indirect effect on absorptive capacity)	Model 3 (direct+indirect effect on knowledge production, γ= 0.1)
Energy R&D	318 % (1.77)	260 % (1.49)	262 % (1.33)
General purpose R&D	4.15 % (1.51)	4.17 % (1.52)	3.92 % (1.26)
Education expenditure	−5.31 % (−5.23)	−5.00 % (−4.97)	−3.30 % (−3.54)
Policy costs (discounted GDP loss)	−1.37 % (−27.9)	−1.32 %(−26.7)	−0.92 %

Summary across different model specifications. Percentage change of cumulative investments compared with BaU (2005US$ trillion in parenthesis). NPV, 5 % discounting

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 labor 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.

4 Coupling Climate and Education Policies

The previous section shows that the way human capital enters into the model affects the induced effect of climate policy. In the introduction we also discuss how the direct and indirect effects of human capital can create synergies between educational and climate change policies. This section looks at the interaction between climate and education policy. Climate policy targets will certainly interact with other policy goals, including objectives related to R&D and education. An example is given by the European Union (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 [62] also emphasized that, to be effective, climate policy should be supplemented by generic socioeconomic development and increased mitigative capacity. This suggests that enhancing education, a determinant of mitigative capacity [30], 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).

To analyze a policy combination of climate and education goals, 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. To compute the additional spending on education in SSA and SASIA we combined the percentage of population off-track[10] from Glewwe et al. [63] with population projections from the WITCH model. We also used the estimates of average spending per student provided by Glewwe et al. [63], 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 Official Development Assistance.[11] The macroeconomic effects of combining education and climate policy are shown in Table 7.

[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.

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

Table 7 Global macroeconomic effects of joint climate and education policies

	Education expenditure (%)	General purpose 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

Basic model with only direct effect (model 1). Percentage changes compared with BaU. NPV using 5 % discounting

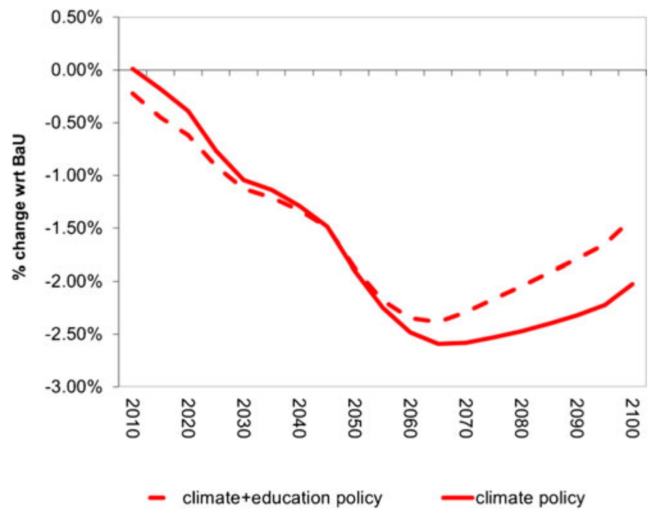

Fig. 4 Consumption path in two policy scenarios using model 1 (direct effects). Percentage changes compared with BaU

Adding the education policy stimulates further innovation, especially general purpose 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. This result is in part due to the elasticities of output and emissions to education investments, shown in Table 4. 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 [64]. 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- and long-term consumption, which is further analyzed in Fig. 4. 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 jeopardize the achievement of the other objective, that of stabilizing GHG concentrations in the atmosphere.

5 Conclusions

This paper has explored the relationship between innovation, human capital, and climate policy by means of a calibrated 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 an innovative modeling assessment of the interplay between two important determinants of economic growth, innovation, and human capital, in the context of climate policy.

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 labor productivity. Using this basic structure, we analyzed the indirect effect of human capital on technological absorption and explored the relationship between human capital and innovation. Using these alternative formulations, we analyzed how climate policy affects both innovation and the accumulation of human capital.

Results indicate that climate policy stimulates investments in energy R&D without reducing those in general purpose R&D if there are complementarities between these two forms of investments. Although general purpose 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 labor productivity have a negative impact on the environment, because labor 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.

Modeling the indirect effect of human capital on absorptive capacity mitigates the crowding-out effect of climate policy, but 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 fully counterbalance the direct impact on labor productivity.

Overall, 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 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.

Appendix: Equations and Variables

WITCH is a dynamic optimal growth model (top–down) with a detailed 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 (USA), 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, oil, and pulverized coal power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with carbon capture and sequestration. Carbon free technologies include hydroelectric and nuclear power, wind turbines and photovoltaic panels (wind and 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 setup 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 behaviors and strategic interactions. The model can produce two different solutions. The cooperative solution is globally optimal, because it maximizes global social welfare and internalizes environmental and economic externalities. It represents a first-best optimum. The decentralized, or noncooperative solution is strategically optimal for each given region (Nash equilibrium), but it does not internalize externalities. It represents a second-best optimum. An intermediate solution that internalizes 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 part 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. [42, 43].

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

$$W(n) = \sum_t L(n,t)\{\log[c(n,t)]\}R(t) \tag{4}$$

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

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

where $\rho(\nu)$is the pure rate of time preference and $c = \frac{C}{L}$ is per capita consumption. The budget constraint defines consumption as output minus investments and operation and maintenance costs in different energy technologies i, (I_i) and ($O\&M_i$) investments in final good (I_c), education expenditure (I_{EDU}), investments in general purpose R&D ($I_{\mathrm{R}}\&_{\mathrm{D}}$) and energy R&D ($I_{\mathrm{ER}}\&_{\mathrm{D},\ j}$) in energy efficiency ($j$=EFF) and backstop technologies (j=BACK):

$$C(n,t) = Y(n,t) - \sum_i I_i(n,t) - \sum_i O\&M_i(n,t) - I_C(n,t) - I_{EDU}(n,t) - I_{R\&D}(n,t) - \sum_{j=EFF,BACK} I_{ER\&D,j}(n,t) \tag{6}$$

Output is produced via a nested CES function that combines capital (K), labor (L), and energy services (EN):

$$Y(n,t) = H(n,t)\Omega \left(A_K(n,t)K(n,t)^{\rho Y} + A_L(n,t)L(n,t)^{\rho Y} + A_{EN}(n,t)\mathrm{EN}(n,t)^{\rho Y}\right)^{\frac{1}{\rho Y}} \tag{7}$$

Neutral technical change (H) evolves exogenously with time. Factor productivity is endogenous and depends on the stock of general-purpose knowledge (R&D), or human capital (HK). Energy productivity is also affected by a dedicated stock of energy knowledge ($\mathrm{R\&D}_{E,\ \mathrm{EFF}}$):

$$A_K(n,t) = A_{K0}(n,t)\left(\frac{\mathrm{R\&D}(n,t)}{\mathrm{R\&D}(n,0)}\right)^{\chi_K}$$
$$A_{\mathrm{EN}}(n,t) = A_{E0N}(n,t)\left(\frac{\mathrm{R\&D}(n,t)+\mathrm{R\&D}_{E,\mathrm{EFF}}(n,t)}{\mathrm{R\&D}(n,0)+\mathrm{R\&D}_{E,\mathrm{EFF}}\left(n,0\right)}\right)^{\chi_E}$$
$$A_L(n,t) = A_{L0}(n,t)\left(\frac{\mathrm{HK}(n,t)}{\mathrm{HK}(n,0)}\right)^{\chi_L} \tag{8}$$

The production of both human capital and knowledge is characterized 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 ($I_{\mathrm{R\&D}}$) are combined to produce the new knowledge capital ($Z_{\mathrm{R\&D}}$). The sum of the exponents is less than one to account for diminishing returns on education and R&D:

$$\begin{aligned} Z_{\mathrm{EDU}}(n,t) &= \alpha_{\mathrm{EDU}} I_{\mathrm{EDU}}(n,t)^{\beta_{\mathrm{EDU}}}\mathrm{HK}(n,t)^{\phi_{\mathrm{EDU}}} \\ Z_{\mathrm{R\&D}}(n,t) &= \alpha_{\mathrm{R\&D}} I_{\mathrm{R\&D}}(n,t)^{\beta_{R\&D}}\mathrm{R\&D}(n,t)^{\phi_{\mathrm{R\&D}}} \\ &\text{where} \\ \beta_{\mathrm{EDU}}+\phi_{\mathrm{EDU}} &< 1 \\ \beta_{\mathrm{R\&D}}+\phi_{\mathrm{R\&D}} &< 1 \end{aligned} \tag{9}$$

The stock of both knowledge and human capital depreciate over time. Following Jorgenson and Fraumeni [65], the depreciation rate of human capital (δ_{EDU}) is lower than the depreciation rate of knowledge ($\delta_{\mathrm{R\&D}}$; 2 and 5 %/year, respectively). The final laws of accumulation read as follows:

$$\begin{aligned} \mathrm{HK}(n,t+1) &= \mathrm{HK}(n,t)(1-\delta_{\mathrm{EDU}}) + Z_{\mathrm{EDU}}(n,t) \\ \mathrm{R\&D}(n,t+1) &= \mathrm{R\&D}(n,t)(1-\delta_{\mathrm{R\&D}}) + Z_{\mathrm{R\&D}}(n,t) \end{aligned} \tag{10}$$

Investments in R&D that build up the stock in Eq. (9) represent the total innovative activity of the economy. Therefore, we also refer to it as general-purpose innovation. Investments in clean energy R&D ($I_{\mathrm{ER\&D},\ j}$) are combined with the existing stock of knowledge ($\mathrm{R\&D}_{E,\ j}$) and the knowledge of other countries ($\mathrm{SPILL}_{E,\ j}$) to produce new dedicated energy knowledge ($Z_{E,\ j}$). The model specifies three different energy knowledge stocks, energy efficiency (j=EFF), and two stocks of breakthrough knowledge, (j=BACK):

$$\begin{aligned} Z_{E,j}(n,t) &= \alpha_{E,j} I_{E\mathrm{R\&D},j}(n,t)^{\beta_{E,j}}\mathrm{R\&D}_{E,j}(n,t)^{\phi_{E,j}}\mathrm{SPILL}_{E,j}(n,t)^{d} \\ &\text{where} \\ \beta_{E,j}+\phi_{E,j}+d &< 1 \end{aligned} \tag{11}$$

with the standard accumulation equation:

$$\mathrm{R\&D}_{E,j}(n,t+1) = \mathrm{R\&D}_{E,j}(n,t)\left(1-\delta_{E,j}\right) + Z_{E,j}(n,t) \tag{12}$$

The contribution of foreign knowledge (SPILL) is not immediate, but depends on the interaction between two terms [59]: 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 high-income countries, denoted with the index HI. They include USA, WEURO, EEURO, CAJANZ, and KOSAU). Domestic investments are required to benefit from the international pool of knowledge.

$$\mathrm{SPILL}_{E,j}(n,t) = \frac{\mathrm{R\&D}_{E,j}(n,t)}{\sum_{\mathrm{HI}}\mathrm{R\&D}_{E,j}(n,t)}\left(\sum_{\mathrm{HI}}\mathrm{R\&D}_{E,j}(n,t)-\mathrm{R\&D}_{E,j}(n,t)\right) \tag{13}$$

The WITCH model includes two backstop technologies. These are innovative, zero-carbon technologies currently not commercialized, because they are 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 modeled with a two-factor learning curve. The unit cost of each backstop technology (P_{BACK}) evolves over time with technology deployment (CC_{BACK}) and the accumulation of a dedicated knowledge stock ($\mathrm{R\&D}_{E,\ \mathrm{BACK}}$):

$$\frac{P_{\mathrm{BACK}}(n,t)}{P_{\mathrm{BACK}}(n,0)} = \left(\frac{\mathrm{R\&D}_{E,\mathrm{BACK}}(n,t-2)}{\mathrm{R\&D}_{E,\mathrm{BACK}}(n,0)}\right)^{-c}\left(\frac{\mathrm{CC}_{\mathrm{BACK}}(n,t)}{\mathrm{CC}_{\mathrm{BACK}}(n,0)}\right)^{-b} \tag{14}$$

R&D stock accumulates with the perpetual rule and with the contribution of international knowledge spillovers as in Eqs. (11) and (12). Equations (4)–(14) describe the basic formulation of the model. Starting from this version, we considered two possible variations. First (model 2, Section 3.2), human capital has an indirect effect on technological absorption and it contributes to increasing the absorptive capacity in the energy sector:

$$\mathrm{SPILL}_{E,j}(n,t) = \frac{\left(\mathrm{R\&D}_{E,j}(n,t)+\mathrm{HK}(n,t)\right)}{\sum_{\mathrm{HI}}\mathrm{R\&D}_{E,j}(n,t)}\left(\sum_{\mathrm{HI}}\mathrm{R\&D}_{E,j}(n,t)-\mathrm{R\&D}_{E,j}(n,t)\right) \tag{15}$$

Second (model 3, Section 3.3), human capital is an input in the creation of both stocks of generic and energy knowledge (for energy efficiency and backstop technologies). Therefore, Eqs. (9), and (11) are modified as follows

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

$$Z_{E,j}(n,t) = \overline{\alpha}_{e,j} I_{E\mathrm{R\&D},j}(n,t)^{\beta_{e,j}} \mathrm{R\&D}_{E,j}(n,t)^{\overline{\varphi}_{e,j}} \mathrm{SPILL}_{E,j}(n,t)^{d} \mathrm{HK}(n,t)^{\gamma_{\mathrm{EDU}}} \tag{16}$$

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 $\overline{\varphi} < \varphi$.

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