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Modeling Biased Technical Change. Implications for Climate Policy

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Summary

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Keywords: Technical Change, Climate Policy, Stabilization Cost

JEL Classification: C72, H23, Q25, Q28

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Abstract

Climate-economy models aiming at quantifying the costs and effects of climate change impacts and policies have become important tools for climate policy decision-making. Although there are several important dimensions along which models differ, this paper focuses on a key component of climate change economics and policy, namely technical change. This paper tackles the issues of whether technical change is biased towards the energy sectors, the importance of the elasticity of substitution between factors in determining this bias and how mitigation policy is likely to affect it. The analysis is performed using the World Induced Technical Change model, WITCH. Three different versions of the model are proposed. The starting set-up includes endogenous technical change only in the energy sector. A second version introduces endogenous technical change in both the energy and non-energy sectors. A third version of the model embodies different sources of technical change, namely R&D and human capital. Although different formulations of endogenous technical change have only a minor influence on climate policy costs, the macroeconomic effects on knowledge and human capital formation can vary greatly.

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1 Technical change: an ongoing debate

Climate-economy models aiming at quantifying the costs and effects of climate change impacts and policies have become important tools for climate policy decision-making. These models reproduce energy and emission scenarios over time and can inform us about the costs of achieving a given stabilization target or the optimal policy path. Modelling results are quite heterogeneous and subject to a significant degree of uncertainty. Although there are several important dimensions along which models differ, this paper focuses on a key component of climate change economics and policy, namely technical change.

Understanding and accurately characterizing the process of technical change is itself a challenging task. The ways in which economic incentives (endogenous technical change) or policy (induced technical change) can modify the pace and the direction of technical change are questions that do not have univocal answers.

The specification of the dynamics of technical change in climate-economy models has received increasing attention from modellers, but, as recently emphasized by Pielke *et al.*, (2008), despite significant improvements, the appropriate way to model technical change is still a matter of debate.

A first tradition of models included the time evolution of technical change, but its determinants were left as exogenous, reflecting the pattern of historical data. Technical change, which is inherently unobservable and has conventionally been represented by proxy variables, was often approximated by a deterministic time trend (Nordhaus and Yang, 1996). Recent modelling efforts have focused on a more comprehensive description of technical change and specific models devoted to investigating induced technical change (ITC) have emerged. Overall, these models show that ITC substantially affects the long run costs of policy and the timing of actions, while broadening the scope of technology-related policies (Grubb *et al.*, 2002).

Nevertheless, most climate-economy models have limited their efforts to endogenise technical change in the energy sector, assuming autonomous trends of other forms of technical change or omitting them. These models implicitly assume that mitigation policies only affect investments in pollution saving technology, and that other forms of technical change play no substantial role. The

natural question to pose is why this should be the case. Whether technical change is energy-saving or energy-using¹ is an empirical question and the evidence supports the existence of both energy-saving and energy-using technical change (van der Werf, 2008; De Cian, 2009). Rising energy prices and more stringent environmental policies are likely to spur innovation especially in the energy field (Jaffe and Palmer, 1997; Popp, 2002), but still other types of innovations (e.g. labour or capital saving) will continue to occur. Moreover, the theoretical literature has shown how technical change is not necessarily pollution-saving, but it can also be pollution-using.

Whether technical change is good or bad for the environment depends on the direction it takes. In order to have sustainable growth, pollution-saving technical change must dominate other types of technical change, such as neutral technical change or labour-augmenting technical change, which tends to increase pollution (Bovenberg *et al.*, 1995; Brock and Taylor, 2004; Lopez, 1994).

In addition, the effects of technical change on production - and thus on the environment - depend on the substitutability among inputs. If technical change increases the productivity of inputs that are a gross complement to emissions, the overall effect of technical change may be to increase pollution (Lopez, 1994). For example, if energy is a gross complement to labour and capital, technical change directed towards those inputs may increase emissions. This indicates the key role played by the elasticity of substitution and the deep interconnections between substitution and technical change (Sue Wing, 2006).

This paper tackles the issues of whether technical change is biased towards the energy sectors, the importance of the elasticity of substitution between factors in determining this bias and how a mitigation policy is likely to affect it. The analysis is performed using the World Induced Technical Change model, WITCH. The model has been modified to allow for factor-augmenting knowledge and to embody different assumptions about endogenous technical change. Three different versions of the model are proposed. The starting set-up includes endogenous technical change only in the energy sector. A second version introduces endogenous technical change in both the energy and non-energy sectors. A third version of the model embodies different sources of technical change, namely R&D and human capital. The analysis shows that there are substantial economic and policy implications of different assumptions about endogenous technical change.

¹ Technical change is *input-saving*, or *input-augmenting*, if the input cost share decreases at constant factor prices. It is *input-using* if the input cost share increases at constant factor prices. Technical change is *neutral* when it does not save relatively more of one of the inputs of production, e.g. the productivity of all inputs is equally increased.

2 Technological change and input substitution: contributions from the empirical literature

From an economic point of view, technological change can be defined as a change in the techniques of production². Quoting Clarke and Weyant (2002) “...*for technology to change, the production function must change...*”. Indeed, the production function can be seen as a mathematical relationship between factors of production and output. There are two key parameters characterizing input-output combinations: (i) the elasticity of substitution and (ii) input efficiency or productivity. Technology parameters may change over time exogenously (exogenous technical change) or with the change of other economic variables such as R&D, international trade and prices.

Climate-economy models represent the production side of the economy through production functions that can be parameterized in different ways, reflecting different assumptions about technology. The production structure, determining the way inputs are nested together, the elasticity of substitution, describing the ease with which inputs can be compensated with each other, and the technology coefficients, characterizing the efficiency of inputs, are the key factors that specify a production function. By shaping the production process, the way technical change is represented in climate-economy models influences the timing, costs and availability of policy options. For example, if energy can be easily substituted with capital or labour, an increase in energy prices induced by climate policies will not have high costs since the expensive input (energy) can be easily replaced with other factors of production.

The production structure adopted by climate-economy models varies from a Cobb-Douglas structure, which is used in many intertemporal growth models, to more flexible structures such as the Constant Elasticity of Substitution production function (CES), originally introduced in Computable General Equilibrium (CGE) models. Nevertheless, large differences exist with respect to the nesting structure used, the size of the elasticities and the way technological change is represented in the production function. While CES production functions allow for different

² Past literature has distinguished technical change from technological change, which is the application of new techniques of production to a broad spectrum of economic activity (Binswanger and Ruttan, 1978). However, current literature, including this paper, uses the two terms interchangeably.

elasticities of substitution among different pairs of inputs, the Cobb-Douglas production function has a major limitation in that it restricts the elasticity of substitution to one.

Equation 1 and Equation 2 provide a simple example of a nested production function. Final output, Y , is produced by a CES combination of capital-labour aggregate, KL , and energy input, E , and capital-labour aggregate is a Cobb-Douglas combination of capital input, K , and labor input, L .

$$Y = [KL^\rho + E^\rho]^{1/\rho} \quad (1)$$

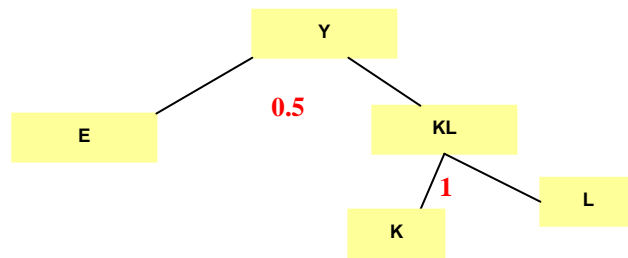
where

$$KL = K^\alpha L^{1-\alpha} \quad (2)$$

The elasticity of substitution, σ , between KL and E , is related to the parameter ρ according to the standard definition $\sigma = \frac{1}{1-\rho}$.

Figure 1 shows the production nest of the same function where σ is set equal to 0.5.

Figure 1. Production nest



The empirical literature on the elasticity of substitution is characterized by heterogeneous results, as recently reviewed in Carraro et al. (2009). Several studies focus on the estimation of the elasticities of substitution between energy, capital and labour in industry (Prywes, 1986; Manne and Richels, 1992; Chang, 1994; Kemfert, 1998; Kemfert and Welsch, 2000, Okagawa and Ban 2008), whereas others look at both industry and different countries (van der Werf, 2008). Overall, most of the estimates reveal that all three inputs - capital, labour and energy - are gross complements, and that the elasticity of substitution between capital and labour is higher than the elasticity of substitution between those inputs and energy (see Table 1).

Table 1. Elasticities of Substitution in Empirical Literature

K/L		L/E	
0.88 ^A	Prywes (1986)	0.88 ^A	Prywes (1986)
0.82 ^M	Kemfert (1998)	0.35 ^A	Chang (1994)
0.793 ^M	Kemfert and Welsch (2000)	0.42 ^M	Kemfert (1998)
0.224 to 0.616 ^A	van der Werf (2007)	0.167 ^M	Kemfert and Welsch (2000)
0.07 to 0.33	Okagawa and Ban (2008)	0.517 to 0.863 ^A	van der Werf (2007)
K/E		KL/E	
0.87 ^M	Chang (1994)	0.4	Manne and Richels (1992)
0.65 ^M	Kemfert (1998)	0.42 ^A	Chang (1994)
0.871 ^M	Kemfert and Welsch (2000)	0.5	Kemfert (1998)
0.804 to 1.000 ^A	van der Werf (2007)	0.698	Kemfert and Welsch (2000)
0.04 to 0.45	Okagawa and Ban (2008)	0.147 to 0.622 ^A	van der Werf (2007)
		0.00 to 0.64	Okagawa and Ban (2008)
KE/L			
0.681 to 1.169 ^A	van der Werf (2007)		
0.00 to 0.94	Okagawa and Ban (2008)		

A and M superscripts denote Allen and Morishima elasticities of substitutions, respectively.

Source (Carraro et al.,2009)

This empirical literature, even if still in its infancy, provides important insights about the choice of the appropriate nesting structure. Kemfert and Welsch (2000), van der Werf (2007) and Markandya and Pedroso-Galinato (2007) all estimate alternative nesting structures of a two-level CES function in order to select those supported by the empirical evidence. Both van der Werf (2007) and Markandya and Pedroso-Galinato (2007) find that the structure in which capital, and labour, L, are nested together and then combined with energy, fits the data better than when capital and energy are nested together and then combined with labour. Nevertheless, van der Werf (2007) could not reject a non-nested structure in which capital, labour and energy can be substituted with the same elasticity. Kemfert and Welsch (2000) find that at a national level the KE-L structure fits the data best, while for industry, most often the KL-E structure performs better.

The empirical evidence on the direction of technical change is scarcer, as most literature has focused on measures of neutral technical change. Two recent contributions have undertaken a more systematic assessment of the direction and the sources of biased³ technical change (van der Werf, 2007; De Cian, 2009). Both papers show that the rate of factor-augmenting technological

³ Binswanger and Ruttan (1978) define input bias as the rate of change in the share of input over production when input and output prices are held constant. By factor-augmenting technical change we refer to an increase in input productivity.

change differs significantly across factors, empirically validating the theory of directed technical change.

3 Technical change in the WITCH model: a trilogy

The World Induced Technical Change Hybrid (WITCH) model (Bosetti *et al.*, 2006; Bosetti *et al.*, 2007) is an Integrated Assessment Model (IAM) designed to deal with the main features of climate change. The model has been developed along three different directions, each featuring different structures of production and sources of technical change. Appendix 1 shows the production nests and the elasticities of substitution of all three different versions.

In its basic set up, endogenous technical change enters only in the energy sector. The other two versions of the model add some complexity to the analysis, by modelling the productivity of non-energy inputs in an endogenous way. Overall the three variants of the model allow not only a deeper understanding of induced technical change, but they represent valuable means to compare the economic and policy implications of alternative assumptions about technical change, leading to important insights.

3.1 WITCH model: the basic set up

3.1.1 Model structure and main features

WITCH is an optimal growth model of the world economy that integrates sources and consequences of climate change in a unified framework. A reduced form climate module (MAGICC) allows for climate factors to feedback to the economic system.

It belongs to the class of hybrid model, embodying features of both top-down (TD) and bottom-up (BU) models. The TD component consists of an intertemporal optimal growth framework, the BU component allows for a representation of the energy sector of average complexity.⁴

⁴ In concrete terms, Top Down and Bottom Up models differ mainly with respect to the representation of the energy system and its interactions with the rest of the economy. Whereas Top Down models represent the whole economic system, Bottom Up models are partial description of the energy sector. This distinction has become increasingly blurred and hybrid efforts, such as the WITCH model, are being developed. Loschel (2002) gives a taxonomy of the different model types.

The world economy is disaggregated into twelve macro regions⁵ that interact strategically in a game theoretical setting. Channels of interactions are the presence of exhaustible resources, knowledge and experience spillovers, and the environment. International knowledge spillovers mimic the flow of ideas and knowledge across countries. Experience in the development of niche technologies such as renewable energy (wind and solar) and breakthrough technologies can also spill over internationally, over a reasonable window of time. In the presence of a climate policy, international emission trading can be simulated, adding an additional source of interaction.

The model can thus produce two different solutions: a cooperative solution, which is globally optimal because the social planner maximizes global welfare, and a non-cooperative solution (Nash equilibrium) which instead is strategically optimal for each single region. The latter solution better reflects the non-cooperative nature of international relations. As a consequence, it does not represent a first best outcome but rather it accounts for economic and environmental inefficiencies arising from the presence of global externalities (emissions, exhaustible resources, knowledge).

Regions face a problem that is economic and environmental. On the one hand, economic agents aim at maximizing welfare, thus consumption and production. On the other hand, production brings about an increase in GHG emissions that ultimately reduce consumption possibilities. In the optimisation process, each region chooses the dynamic mix of investments in capital stocks, innovation and energy technologies so as to optimally balance these two opposing forces.

Following the framework of neoclassical growth models, a unique final good is produced and employed for alternative uses (consumption, investments, reducing climate change damage). Production is characterized as a nested CES. At the top-nest level, the substitution possibilities between capital and labour are described by a Cobb-Douglas production function. The capital-labour nest can then be substituted with energy services. The lower flexibility in substitution between the capital-labour nest and energy is reflected in a low elasticity of substitution (0.5).

The only source of endogenous technical change appears in the energy sector, whereas increases in total factor productivity remains exogenous. Energy services are the result of a combination between raw energy and a stock of energy efficiency knowledge. This form of endogenous

⁵ The twelve regions are USA (United States), OLDEURO (Western Europe), NEWEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJAZ (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)

technical change captures improvements in overall energy efficiency in the economy and energy knowledge can substitute the use of the physical input. The flow of new ideas results from the combination of investment in R&D and the stock of cumulated knowledge, and contributes to increase the current stock of knowledge.

A wide set of different technologies, ranging from traditional coal/oil/gas power plants to carbon free options such as nuclear, renewables and biofuels, can be used in the generation of energy. The model also features new generation technologies - referred to as breakthrough technologies - which can become competitive in a few decades, provided sufficient investments in dedicated R&D are undertaken. Endogenous technical change in the energy sector can be driven by both Learning by Doing (LbD) and Learning by Researching (LbR). Both experience (LbD) and innovation (LbR) can bring down investment costs in specific technologies.

3.1.2 Climate policy: implications for the optimal investment mix

Contrary to most top-down macroeconomic models, WITCH features a portfolio of mitigation options that can be used to achieve low carbon scenarios. Key mitigation options include nuclear power, Carbon Capture and Sequestration (CCS), renewables and biofuels. Moreover, energy efficiency can improve endogenously with energy innovation and the deployment of breakthrough technologies can become competitive with a sufficient amount of targeted R&D.

In this setting, the carbon price is an important signal that provides the right stimulus for investment in R&D targeted to enhance energy efficiency and to increase the competitiveness of innovative low carbon technologies.

When a stringent climate policy is implemented, the world carbon price⁶ increases rapidly in the first half of the century when a stronger signal is needed to stimulate an optimal reallocation of resources towards low carbon technologies (Table 1). This carbon pricing induces a four-fold expansion of energy R&D investments, raising the fraction of gross world product invested in energy innovation from 0.02% up to 0.08%, the peak level reached in 1980 after the oil price

⁶ This is the world carbon price that emerges in the international carbon market when a 450 ppm long-run CO₂ concentration stabilization target is imposed.

shock. A carbon price signal consistent with a 450 ppm CO₂ concentration stabilization target also induces large investments in low carbon technologies such as renewables, nuclear and CCS.

Additional investments in innovation and low carbon technologies come at the cost of overall economic growth, especially in the first half of the century when more effort is needed to bring in breakthrough technologies. The economic losses computed in terms of Gross World Product (GWP) and its variation over time are displayed in Table 1.

Table 1. Climate policy effects: carbon price and macroeconomic costs

	2025	2045	2065	2085	2105
GWP					
(Percentage change with respect to the baseline scenario)	-1.09%	-2.00%	-3.37%	-2.21%	-0.16%
Carbon Price (USD/tCO₂)	35	283	810	1083	1179

3.2 Introducing Directed Technical change

The WITCH model as formulated in Bosetti et al. (2006) is an important contribution to the climate-economy literature as it presents a detailed treatment of the process of energy innovation and diffusion of both knowledge and experience. However, the modelling approach to technical change can be considered “partial” in that it abstracts from other forms of innovation that may occur outside the energy sector and affect the overall macroeconomic structure.

More precisely, non-energy R&D expenditure is not explicitly modelled, instead it is included in the economy-wide investment variable, and an exogenous crowding out of investments by energy R&D expenditures is assumed to take into account the alternative and competitive uses of R&D funds.

However, as emphasized by Goulder (2004) it is not possible to rule out that forces other than the “crowding out” effect may lower investments in other sectors and turn a de-carbonized economy into a less technologically advanced economy. For example, Goulder and Schneider (1999), Sue Wing (2003) and Gerlagh (2008), all find that climate policy induces substantial changes in total R&D investments and not only in the energy sector. Which forces mould such changes and how those changes affect the cost of policy are still open questions.

Also, as emphasized by Acemoglu (2002), technical change is not neutral. Since it is not possible to exclude the possibility that technical change in non-energy sectors affects energy demand, the direction of technical change and whether or not it is biased towards energy may have important implications for climate policy⁷.

3.2.1 Model structure and main features

With the goal of addressing questions about the impact of a long-term GHG stabilization policy on the direction and bias of technical change, and inspired by the contribution of Acemoglu (2002), the WITCH model has been modified to introduce factor-specific technical change.

A non-energy R&D sector, which enhances the productivity of the capital-labour aggregate, has been added to the energy R&D sector. By explicitly modelling directed technical change we can investigate whether technical change is biased and if a climate policy is likely to reverse that bias. Also, by relaxing any assumptions of exogenous crowding out between R&D sectors, we totally endogenize the impact of a strong mitigation policy on the rate of technical change both at sectoral and aggregate levels, and we are then in a position to disentangle those effects - other than crowding out – which affect the reallocation of investments in knowledge.

As specified above, gross output is obtained from a combination of energy services produced by the energy sector and capital-labour services produced in the non-energy sector, but with a different nesting structure of production. Two main modifications have been made. First, the Cobb-Douglas combination of capital and labour inputs is replaced with a CES nest. The elasticity of substitution between labour and capital, σ_{KL} , is now set lower than 1 and equal to 0.8, as suggested by the empirical evidence described in Table 1. Secondly, a new stock of knowledge that can enhance the productivity of capital-labour services is introduced. The resulting production structure therefore includes two input-specific knowledge stocks that characterize the productivity of energy and the capital-labour nest in an endogenous way. The production of new ideas and the evolution of the knowledge stock in the non-energy sector are characterized by intertemporal spillovers and decreasing returns, like the energy sector as described in Bosetti et al. (2006).

⁷ Following Acemoglu (2002) technical change is input-biased if it increases the marginal productivity of one particular input relative to other inputs.

From the baseline scenario – which corresponds to the non-cooperative Nash equilibrium of the WITCH model under the assumption of no mitigation policy – we obtain the equilibrium investment trajectories, together with the equilibrium R&D investments, GWP and consumption path. The optimal equilibrium paths of R&D investments make it possible to analyze the predictions of the model about the direction of technical change.

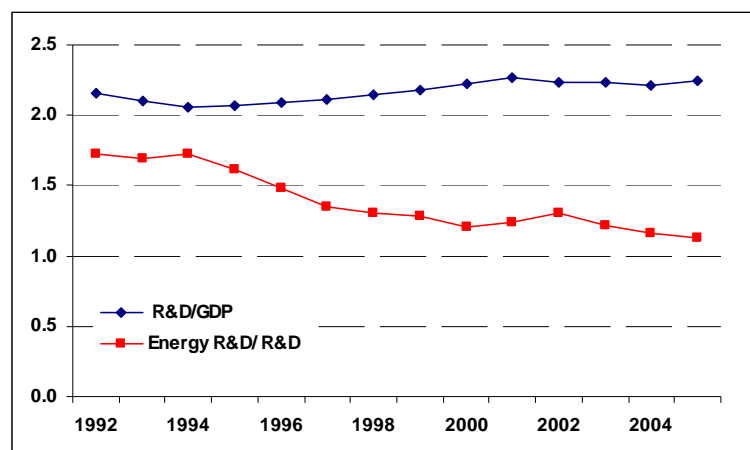
Table 2. Baseline Trends in R&D Investments

	2005	2025	2045	2065	2085	2105
Total R&D (%GWP)	1.93%	2.04%	2.06%	2.05%	2.00%	1.84%
Non-energy R&D (%GWP)	1.92%	2.03%	2.04%	2.03%	1.98%	1.83%
Energy R&D (%GWP)	0.018%	0.017%	0.016%	0.016%	0.015%	0.014%
Energy R&D (%Total Investment in R&D)	0.93%	0.82%	0.79%	0.77%	0.76%	0.75%

Table 2 shows that R&D investments as a percentage of Gross World Product (GWP) slightly increase across the century. This is mainly due to a gently increasing investment path in non-energy R&D while energy R&D investment is slightly decreasing.

This result is in line with historical trends displayed in figure 1. Historical data for OECD countries shows a trend over the past 13 years of slightly increasing total R&D investment over GDP, starting from 2.15% in 1992 and reaching 2.25% in 2005, and a decreasing path of energy R&D over total R&D investment, starting from 1.7% in 1992 and dropping to 1.1% in 2005.

Figure 1. R&D as a Percentage of GDP and Energy R&D as Percentage of Total R&D (OECD countries)



According to the outcomes of the model, technical change is mainly capital-labour augmenting and - most importantly - energy-biased because, as found by empirical studies and assumed in the model, the capital-labour aggregate and energy are complements. This means that R&D investments are mainly directed towards the capital-labour aggregate, but they also increase the productivity of the energy input relative to the productivity of the capital-labour aggregate. As a consequence, any increase in the stock of non-energy knowledge triggers an increase in energy demand.

3.2.2 Climate policy: impacts on the direction and magnitude of technical change, and on policy costs

In most climate-energy models which include endogenous technical change, the implementation of climate policy induces technical change in carbon saving technologies, but as emphasized above, the impact on other R&D sectors and on the overall rate of technical change is often omitted. By including directed technical change we are in the position to analyze the effect of the stabilization policy on the overall rate of technical change and to compare this result with the standard version of the model to see how different assumptions about technical change affect the cost of the policy.

When the stabilization target is implemented investments are made in the energy sector to accelerate the deployment of carbon-free technology and to increase energy efficiency by augmenting energy R&D capital stock. As shown in table 3, we find that climate policy strongly re-directs investment to energy R&D. The opposite is true for the non-energy sector where the share of non-energy R&D investment declines more and more. Overall, since induced technical change in the energy sector is not enough to compensate the contraction of investment in capital-labour knowledge, the rate of technical change of the economy slows down. The stabilization policy has thus strongly affected the rate of knowledge accumulation and the economy becomes less and less knowledge intensive.

Table 3. Stabilization Trends of R&D Investments – Percent changes w.r.t. the baseline scenario

	2025	2045	2065	2085	2105
Total R&D (%GWP)	-3.78%	-6.90%	-8.14%	-7.87%	-7.03%
Non-energy R&D (%GWP)	-4.36%	-7.87%	-9.14%	-8.75%	-7.79%
Energy R&D (%GWP)	66.71%	116.25%	121.04%	107.76%	93.79%
Energy R&D (%Total Investment in R&D)	1.42%	1.83%	1.86%	1.71%	1.56%

As shown in detail by Carraro *et al.* (2009) the reduction of the rate of investments in non-energy R&D does not result from a crowding out effect due to increased investment in energy R&D - as is often proposed in the literature - instead, it depends on the structure of the economy, as portrayed in the model. Since capital-labour augmenting technical change is energy-biased, when an ambitious climate policy is implemented, one channel to reduce energy demand, and therefore emissions, is by slowing down the pace of pollution accumulation by augmenting the knowledge stock.

This result has important implications for the cost of policy. While omitting ITC in the Energy sector usually overestimates the cost of policy in terms of Gross World Product losses, omitting endogenous technical change in the non-energy sector actually underestimates it, because the negative impact of the climate policy on the rate of technical change of the entire economy is ignored.

3.3 Introducing Human Capital

In the WITCH model with endogenous energy technical change (Bosetti *et al.* 2006) and in the version with directed technical change (Carraro *et al.* 2009) the engine of endogenous technological change is the same: innovation, fuelled by expenditure in R&D. Another important source of endogenous growth is human capital (Lucas, 1988). Despite the existence of theoretical contributions about the relationship between human capital and growth on the one hand (Blankenau and Simpson, 2004) and human capital, innovation and the environment on the other (Gradus and Smulders, 1993; Hettich, 1998; Pautrel, 2008; Grimaud and Tournemaine, 2007; Ikazaki, 2006), the applied climate-economy literature has overlooked other forms of knowledge such as human capital.

These theoretical contributions highlight how the relationship between environmental policy, human capital formation and economic growth hinges on the way human capital and education

come into the model (in the utility function or as a production input) and on what is the source of pollution (output or inputs such as physical capital). When pollution depends on output, an environmental tax tends to reduce wages and thus education spending, with negative implications for human capital formation (Hettich, 1998; Gradus and Smulder, 1993). Instead, when pollution depends on capital, an environmental tax would increase wages relative to the rate of capital return, which boosts education investments.

Education spending can increase growth, but general equilibrium effects may crowd out other sources of growth, such as investments in physical capital and private human capital. The dimension of this crowding out effect depends on, among other things, how education expenditure is financed (Blankenau and Simpson, 2004). When education is financed with consumption taxes, the effects on growth are always positive.

Introducing human capital into the WITCH model as an additional source of endogenous growth makes it possible to assess the interplay between innovation, human capital and climate change policies.

3.3.1 Model structure and main features

The WITCH model version with human capital (Carraro et al. 2008) builds upon recent empirical results (De Cian, 2009) which support the hypothesis that the sources of directed technical change are input-specific. Whereas human capital is an important driver of labour productivity, innovation, measured as the aggregate stock of knowledge, tends to enhance more capital and energy productivity, with a larger impact on the latter.

These findings have been fed back into the WITCH model by amending the top-level nest of the production function. Following the structural model estimated in De Cian (2009)⁸, the three inputs are assumed to be substitutable with the same elasticity (non-nested production function). The productivity of each factor is described by a multiplicative input-specific coefficient. In other words, total factor productivity, which is exogenous in Bosetti et al. (2006), is now decomposed into endogenous factor productivities. Factor productivity - or factor-augmenting technical change

⁸ The dynamics of factor-augmenting technical change have been inferred by observing the time and spatial variation of conditional input demands, derived from an aggregate non-nested production function.

- consists of two elements. An exogenous component, which captures the spontaneous time evolution of technical change, and an endogenous term, which links factor productivity to the economic variables identified in the empirical work.

Capital and energy productivity are a function of knowledge, represented by the stock of aggregate R&D. Labour productivity, on the other hand, is related to human capital, which is approximated by the stock of total expenditure (both private and public) on education.

The production of both human capital and knowledge is characterized by intertemporal spillovers, which is similar to the specification used in Bosetti et al. (2006) and Carraro et al. (2009). The explicit representation of human capital makes it possible to account for the cross effects between innovation and human capital and therefore human capital contributes also to the formation of knowledge.

The resulting framework therefore includes not only energy-saving technical change, as in Bosetti et al. (2006) but also energy-using technical change, as in Carraro et al. (2009). The crucial element driving the implications of technical change for energy, and thus emissions, is the complementarity between inputs. Education investments, directed to improve the productivity of labour, have an effect that is pollution-using because more productive labour is complemented by more energy input. This feature is the main driver behind the implications of climate policies.

3.3.2 Climate policy: implications for knowledge and human capital formation

The implications of a climate policy⁹ for the energy sector and energy-saving innovation are similar to those that can be obtained with the other two versions of the model. The carbon price signal reallocates resources towards low carbon technologies (nuclear, CCS and renewable energy) and energy-saving R&D.

Contrary to what can be observed using the WITCH model with directed technical change, climate policy stimulates a dedicated form of energy-knowledge without reducing total R&D investments. The reason behind this result is the twofold effect of total R&D. Total R&D increases both capital and energy productivity. The first effect (that on capital) is pollution-using, but it is dominated by

⁹ The climate policy is a stabilization target aimed at stabilizing CO₂ concentrations at 450 ppm.

the effect on energy productivity, which is energy-saving. Consequently, climate policy increases total R&D because its energy-saving effect is dominant.

What are the implications for human capital formation? As mentioned above, advancements in labour productivity will have a negative impact on the environment because labour is a complement to energy. Education, which is the engine of human capital accumulation, is pollution-using and therefore when there is a stringent climate constraint, investments are re-directed away from education.

As discussed in Hettich (1998), the effect of an environmental policy on human capital depends on how pollution is modelled and on how education comes into the model. When pollution (in this case emissions) is linked to final output, as is the case in the WITCH model, a tax on emissions reduces the return on both capital and wages, reducing the incentive to invest in education as well.

The negative effect of climate policy on human capital formation is lessened when the contribution of education to the formation of innovation is sufficiently large. In this case, human capital is also pollution-saving, because of the indirect effect on energy productivity. Table 4 summarizes the effects of climate policy on human capital and knowledge. Climate policy tends to reallocate productive resources from energy-using sectors (education) to energy-saving sectors (total R&D). As a consequence, the ratio of total R&D expenditure to education is higher in the presence of climate policies and it increases over time.

Table 4. Stabilization Trends of R&D and Education Investments – Percentage changes w.r.t. the baseline (no policy) scenario

	2025	2045	2065	2085	2105
Total R&D (%GWP)	1.95%	3.84%	3.75%	3.86%	4.26%
Education (%GWP)	-1.31%	-2.82%	-4.56%	-5.18%	-5.63%
Total R&D/Education	3.92%	8.40%	12.05%	13.26%	13.83%

5 Concluding Remarks

The analysis that has been proposed in this paper focuses on the impacts of climate policy on the structure of the economy. Whereas the issue of policy costs has been analyzed at length, less

attention has been paid to structural changes that may be induced by climate policy. The trilogy of modelling approaches to endogenous technical change proposed in this paper has shown how climate policy can have different impacts on innovation and human capital formation.

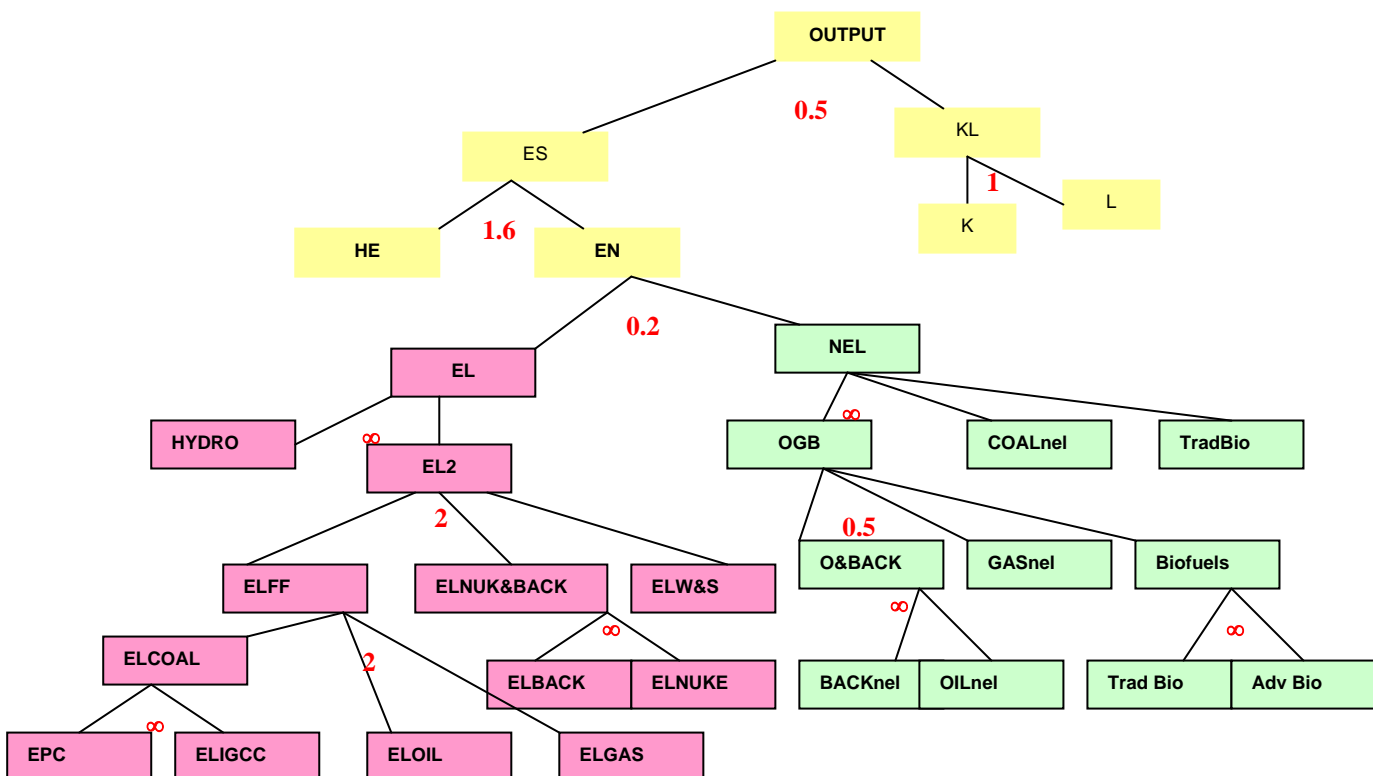
Although different formulations of endogenous technical change have only a minor influence on climate policy costs, the macroeconomic effects on knowledge and human capital formation can vary greatly.

As soon as technical change is allowed to take different directions endogenously, other factors overlooked by state-of-the-art climate-economy literature come into play. In particular, complementarity among factors determines the direction of induced technical change. Given the complementarity between energy on the one hand, and labour and capital on the other hand, any form of technical progress that increases the productivity of the capital-labour nest is energy-using and therefore has negative implications on the environment.

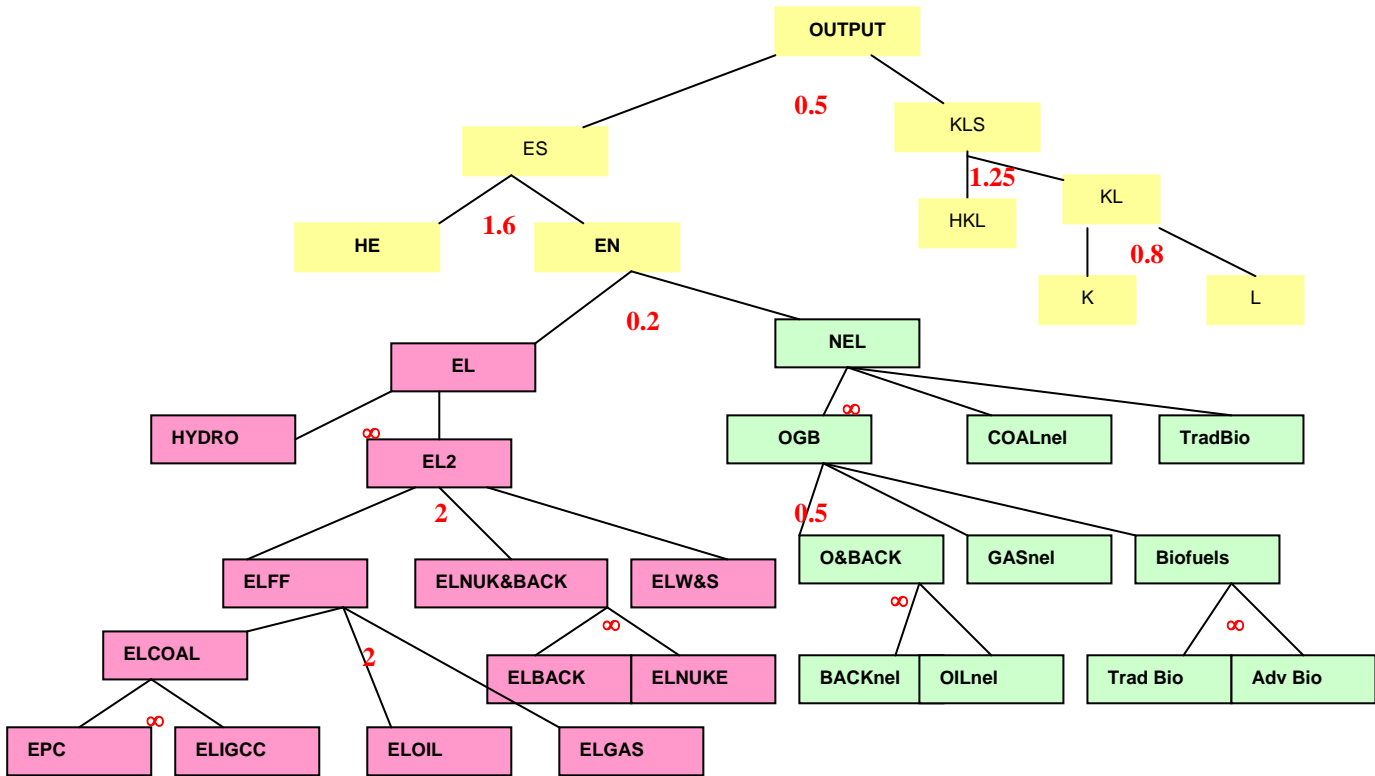
Since climate policy tends to reallocate productive resources from energy-using sectors towards energy-saving sectors, both the accumulation of pollution-augmenting knowledge stock and human capital formation slow down. Although a stabilization policy provides stimulus for energy-saving innovation, the overall effect can be a reduction of the knowledge and human capital intensity of the economy.

Appendix A: The Production Nests and the Elasticities of Substitution.

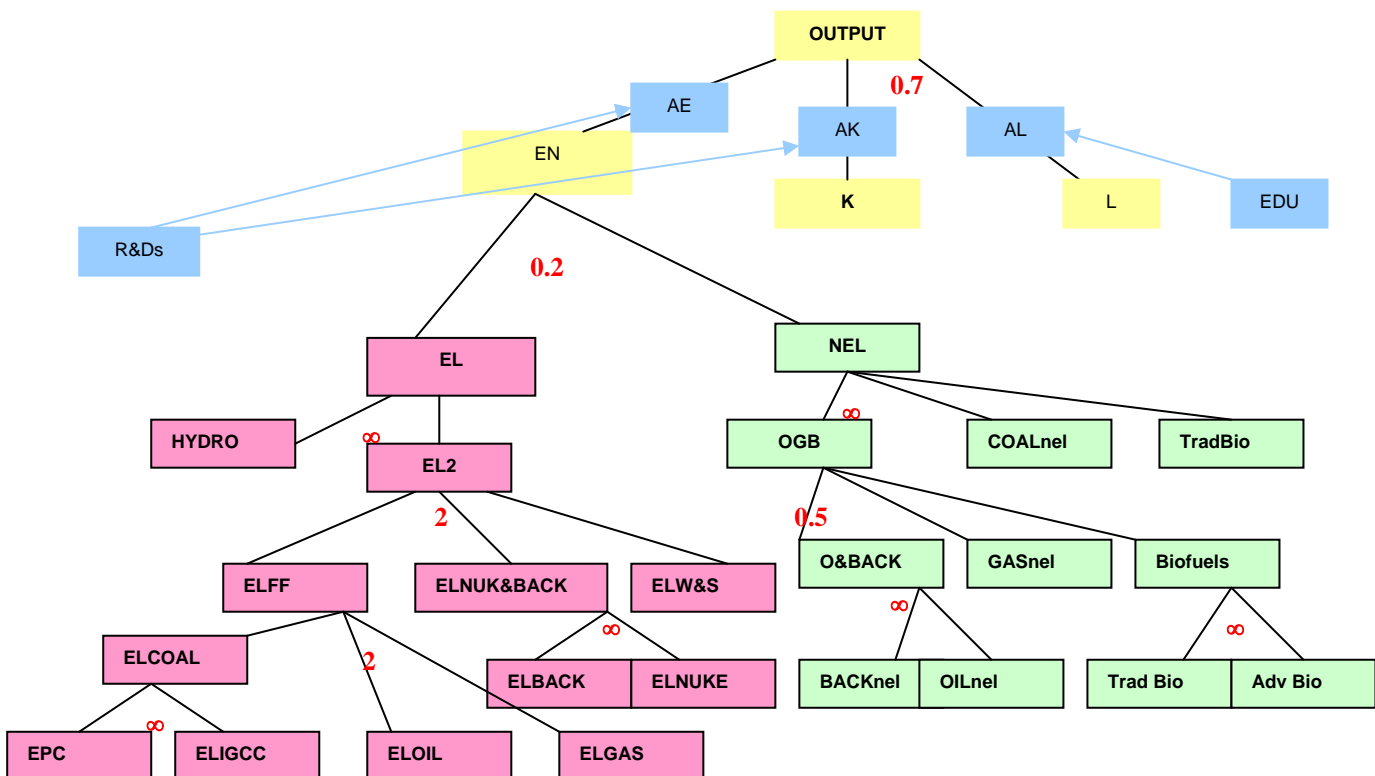
WITCH: basic set-up



WITCH: directed technical change



WITCH: human capital



Model variables are denoted with the following symbols:

Y = production - output

K = final good stock of capital

ES = energy services

KLS = capital-labor services

KL = capital-labor aggregate

HE = energy knowledge

EN = energy

EL = electric energy

NEL = non-electric energy

OGB = Oil, Gas and Biofuel nest

ELFF = Fossil fuel electricity nest

W&S = Wind and Solar

EL $_j$ = Electricity generated with the technology j

TradBiom = Traditional Biomass

K $_j$ = Capital for generation of electricity with technology j

O&M $_j$ = Operation and Maintenance costs for generation of electricity with technology j

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