A MERGE Model with Endogenous Technological Change and the Cost of Carbon Stabilization

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This paper is one of a series published by FEEM on the theme of innovation modeling in the context of the challenge of stabilising atmospheric concentrations of greenhouse gases, as part of the Innovation Modeling Comparison Project. This is an international project launched and overseen by the Steering Committee of the informal International Programme on the Economics of Atmospheric Stabilisation. The broad aim of the collaboration is to advance understanding of the economic issues surrounding atmospheric stabilisation, and the specific aims of the IMCP are to provide insights into the "state of the art" and implications of endogenous modeling of technical change in global energy-environment models when applied to various levels of atmospheric stabilisation.

Members of the Steering Committee provided review comments on earlier drafts and the paper has been forwarded to external review, the final results will be published as a Special Issue of the Energy Journal. The papers have all been encouraged to draw on a common baseline (the "Common Poles-Image baseline") and to report results in comparable formats, so as to facilitate intercomparison of the different modeling results. All the results and judgements expressed here remain the responsibility of the authors.

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Summary

Two stylized backstop systems with endogenous technological learning formulations (ETL) are introduced in MERGE: one for the electric and the other for the non-electric markets. Then the model is applied to analyze the impacts of ETL on carbon-mitigation policy, contrasting the resulting impacts with the situation without learning. As the model considers endogenous technological change in the energy sector only some exogenous key parameters defining the production function are varied together with the assumed learning rates to check the robustness of our results. Based on model estimations and the sensitivity analyses we conclude that increased commitments for the development of new technologies to advance along their learning curves has a potential for substantial reductions in the cost of climate mitigation helping to reach safe concentrations of carbon in the atmosphere.

Keywords: Climate change stabilization policies, Non-linear optimization, Induced technological change, Energy and macroeconomy

JEL Classification: C61, O30, Q42, Q43

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1. Introduction

The Innovation Modelling Comparison Project (IMCP) is an effort to present the state of the art in modelling technological change. The project brings together a variety of different approaches to the inclusion of technological change in global macroeconomic, Integrated Assessment and energy system models. In particular, the project aims to compare and contrast the cost and investment time-paths that could lead to stabilization at 450, 500, 550 ppmv carbon dioxide by 2100, and to explore sensitivities to different modelling approaches and technical assumptions. The PSI group has developed for the Swiss NCCR-Climate Program on "Climate Variability and Risk" Integrated Assessment Models (IAMs) to simulate policies to aid in climate-change mitigation. We report herein model changes and results from a version of MERGE, Manne et al. (1995), Kypreos (2000), Manne and Richels (2002), Kypreos (2005) that supports endogenous and induced technological learning in the energy sector.

The study reported herein is an effort to evaluate the economic advantages of endogenous learning *via* RD&D spending in support of carbon-free energy technologies. The method presented investigates R&D support and learning investments in carbon-free systems to aid these technologies to follow their learning curves. This dedicated RD&D spending could influence developments during the demonstration and deployment phases and reduces the cost of new technologies. We assume that R&D spending together with learning investments creates path dependent knowledge that is diffused on the global level *via* market uptake of these fundamentally different technological systems. We also expect that the increased sales of these advanced systems introduced under a global carbon constraint will induce technological change and significantly reduce the cost of carbon mitigation.

As this special issue gives an overview concerning the state of the art on modeling technological change we focus herein on the problems realized when RD&D spending is introduced as decision variable in hybrid optimization models with perfect foresight. Some first studies applying optimization models introduced by Barreto and Kypreos (2004), Bahn and Kypreos (2002) produced a restricted level of R&D investments reported as needed to support new and advanced technologies. On the contrary, simulation models with adaptive expectations, Criqui et al. (2000) and Kouvaritakis et al. (2000) do not indicate such behaviour. This article presents this version of MERGE that overtakes the difficulty.

Section 2 discusses the new version of MERGE that defines RD&D as decision variable and the assumptions on which costs, emissions, and learning characteristics of technologies that compete in the energy markets are based; this section also explains the formulation of the two factor learning curve (TFLC) model, together with the introduction of subsidies in MERGE. We consider scenarios related to a stabilization of CO_2 concentrations in the atmosphere when including (or excluding) technological learning. Section 3 then reports on this numerical application, and describes impacts of modelling endogenous technological progress in the MERGE environment. Section 4 performs a sensitivity analyses on the most critical input parameters to test the robustness of results. Finally, section 5 concludes with an elaboration of the importance of policies that foster endogenous technological learning while the Appendix describes in some details the calibration and the sensitivity analyses with MERGE.

2. Modelling framework

2.1 MERGE

The **m**odel for **e**valuating **r**egional and **g**lobal **e**ffects (MERGE) is an integrated assessment model (IAM) that provides a framework for assessing climate-change management proposals. We apply the MERGE5 version described by Manne and Richels (2002), which already includes some generic technologies capable of learning-by-doing (LBD), but we model both learning-by-searching (LBS) and learning subsidies. The world modelled in MERGE is divided into nine geopolitical regions: Canada, Australia and New Zealand (CANZ); China; eastern Europe and the former Soviet Union (EEFSU); India; Japan; Mexico, and OPEC (MOPEC); western Europe (WEUR); the United States of America (USA); and the rest of the world (ROW).

An ETA-MACRO model describes each of these nine regions. The ETA component is a ‘bottom-up’ engineering model; it describes the energy-supply sector of a given region, including the production of non-electric energy (fossil fuels, synthetic fuels, and renewables) as well as the generation of electricity. The ETA model captures price-dependent substitutions of energy forms (*e.g.*, switching to low-carbon fossil fuels) and energy technologies (*e.g.*, the use of renewable-energy power plants instead of fossil-fuel systems) to achieve specified CO_2 reduction targets.

MACRO is a ‘top-down’ macro-economic growth model that balances the non-energy part of the economy of a given region using a nested constant-elasticity-of-substitution (CES) production function. The MACRO model also captures autonomous (*e.g.*, price-independent) effects and macro-economic feedbacks between the energy sector and the rest of the economy, such as the impacts of higher energy prices (*e.g.*, resulting from CO_2 control) on economic activities. The mathematical formulation of regional ETA-MACRO sub-models translates into a non-convex, non-linear, optimization problem, where the economic equilibrium is determined by a single optimization. Finally, inclusion of a simple climate and damage model makes MERGE an Integrated Assessment Model. MERGE considers market (through production losses), and non-market damages (through losses in global welfare).

The model maximizes a welfare function defined as the net present value of the logarithm of regional consumption adjusted for the non-market damages. Included in the wealth of each MERGE region are initial endowments in fossil fuels, renewables, and CO_2 emission permits.

MERGE links the regional ETA-MACRO sub-models, and aggregates the regional welfare functions, adjusted for the non-market damages, into a global welfare function using appropriate Negishi weights (Negishi, 1972). Global trade constraints applied in each period ensure that international trade of commodities is balanced. Regional technological learning with global spillovers, climate-change impacts and the associated market and non-market damages further enhance the regional links and interactions.

2.2. Technology Description

Table 1. Technologies used in MERGE5 and naming conventions

Electric	**technologies**	Introduction date	Gen. Cost mills/kWh	Carbon Emissions kg C/kWh
HYDRO	Hydroelectric, and other renewables	Existing	40.	0.0
NUC	Remaining initial nuclear	Existing	50.	0.0
GAS-R	Remaining initial gas fired	Existing	35.7	0.1443
OIL-R	Remaining initial oil fired	Existing	37.8	0.2094
COAL-R	Remaining initial coal fired	Existing	20.3	0.2533
GAS-N	Advanced combined cycle (AGC)	2000	30.3	0.0935
GAS-A	Gas-Fuel Cell with removal	2020	47.7	0.0
COAL-N	Pulverized Coal	2000	40.6	0.1955
COAL-A	Coal-FC with CO2 recovery	2020	55.9	0.0068
IGCC	IGCC with CO2 removal	2020	62	0.024
ADV-HC	Carbon-free technologies, high cost	Existing	95	0.0
LBDE*	Generic back-stop with LBD	2010	95	0.0
Non-Electric	**technologies**			
			US$/GJ	tons C/GJ
CLDU	Coal direct use	Existing	2.5	0.0241
OIL1-OIL10	Oil categories	Existing	3-5.25	0.0199
GAS1-GAS10	Gas categories	Existing	2-4.25	0.0137
SYNF	Synthetic fuels	Existing	8.33	0.04
RNEW	Renewables	Existing	6.	0.0
NEB -HC	Renewables Back-stop, high cost.	Existing	14.	0.0
LBDN*	Generic back-stop with LBD	2010	14.	0.0

*) The two technologies with LBD become available in 2010 once sufficient RD&D investments will be made, otherwise are not available at all. Also, their penetration rates increases and their production cost is assumed to reduced due to RD&D spending.

Technological learning describes how the specific cost of a given technology is reduced through the accumulation of knowledge. This learning process evolves either from manufacturing and operation of the technology (LBD) or research-and-development (LBS) expenditures allocated to that technology. A learning curve relates the specific cost incurred by a given technology to one or more factors describing the accumulation of knowledge in that technology.

Specific components of the energy technologies are treated as generic; for instance, high-cost (ADV-HC) and low-cost (ADV-LC) carbon-free power plants, or plants producing low-cost, non-electric energy from renewables (RNEW) are identified. Table 1 lists the technologies modelled in MERGE, with, the first generic learning technology corresponding to power generation and the second technology referring to a non-electric energy system.

We assume for LBD that a 20% cost reduction is incurred for each doubling in production, and a 15% cost reduction for each doubling in the knowledge stock. Also, a barrier is introduced to represent a maximum possible reduction of generating cost of (*e.g.*, 40 mills per kWh for electric backstop systems and 6 US$/GJ for the non-electric backstops). Electric-generation backstop technologies consist of renewable sources, like wind, solar PV and biomass, new nuclear concepts and carbon capture and sequestration[1]. Non-electric energy-generation/carrier backstops are identified with the

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[1] CCS systems are explicitly introduced in the technological options listed in Table 1 but as learning is not adopted for technologies other than the back-stop systems, CCS systems are not explicitly introduced in the solution.

use of methanol or hydrogen fuels, while the primary-energy sources for these non-electric energy carriers are either biomass or renewable electricity or nuclear (*i.e.*, a carbon-free non-exhaustible energy form). All technologies and the non-learning costs associated with these backstop systems are assumed to be encompassed in an autonomous cost reduction at a rate of 0.2% per annum.

2.3 The Two Factor Learning Curve

In the two-factor learning curve, the cumulative production (output) is used as a proxy for the accumulation of experience that affects the specific investment cost of a given technology. Similarly, the knowledge stock, defined as the accumulation of a depreciated *R&D* spending, is used to determine cost reductions attendant LBS processes. The learning curve for the generation cost $GC_{k,t}$ (in US$ per MWh for electric or US$ per GJ for non-electric) of a technology *k* is then defined as:

$$GC_{k,t} = a \cdot CP_{k,t}^{-b} \cdot \mathrm{KS}_{\mathrm{k,t}}^{\mathrm{-c}} \tag{1}$$

with the knowledge stock $KS_{k,t}$ estimated as the depreciated sum of annual *AR&D*

$$KS_{k,t} = \mathrm{KS}_{\mathrm{k,t\text{-}1}} \cdot (1-\mathrm{s}) + A\mathrm{R\,\&\,D}_{\mathrm{k,t}} \cdot \mathrm{ypp}_{\mathrm{t}} \tag{2}$$

where *s* is the depreciation factor (e.g., 3 percent per year) and *ypp* the number of years per period.

The parameter *a* can be calibrated by applying equation (1) for the initial point $(GC_{k,0}, KS_{k,0}, CP_{k,0})$ of the learning curve, and the parameters *b* and *c* are the learning indices. The latter define the speed of learning and are derived from the learning ratio. The learning ratio *lr* is the rate at which the generating cost declines (e.g., 20%) each time the cumulative capacity doubles, while *lrs* is the rate at which the cost declines each time the knowledge stock doubles. The relation between *b, c, lr* and *lrs* can be expressed as follows:

$$1 - lr = 2^{\mathrm{-b}} \quad \text{and} \quad 1 - lrs = 2^{\mathrm{-c}} \tag{3}$$

The model assumes that both "learning" and "knowledge" diffuse to the entire world and eventually create positive externalities. For the changes in the model, a few new variables and equations are defined. The new variables refer to the annual research and development (*AR&D*) spending, the knowledge stock (*KS*) and the amount of subsidized production (*SPE*). The cumulative production of electricity (*CP*) is based on the annual generation of unsubsidized *PE,* and subsidized electricity, *SPE.*

$$\mathrm{CP}_{\mathrm{k,t}} = \mathrm{CP}_{\mathrm{k,t\text{-}1}} + (\mathrm{PE}_{\mathrm{k,t}} + SPE_{k,t}) \cdot ypp_t \tag{4}$$

The learning curve is coded directly as a non-linear and non-convex formulation according to equation (5), e.g., as function of the cumulative production and the knowledge stock relative to the starting year[1]. The CONOPT3 optimizer defines directly

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[1] The initial annual energy R&D is 360 million US$ equally divided for electric and non-electric backstop technologies. The assumed initial knowledge stock is 8 times the annual spending with a maximum annual growth rate in R&D of 5 percent. The depreciation rate of knowledge is 3% per year.

the global optimal solution in the case that terminal conditions are defined such that local optima are excluded, as explained by Manne and Barreto, (2004).

$$\frac{GC_{k,t}}{GC_{k,0}} = \left(\frac{CP_{k,t}}{CP_{k,0}}\right)^{-b} \cdot \left(\frac{KS_{k,t}}{KS_{k,0}}\right)^{-c} \tag{5}$$

The budget equation of MERGE is re-formulated to take into account R&D spending and the subsidies in learning investments. We assume that knowledge creates positive externalities due to spillovers across different production firms and regions. We also assume public support via subsidies (e.g., learning investments) in the early stage of technology implementation. If the subsidized backstop systems become competitive in the markets their cost decreases with time based on LBD and LBS. Equation (6) describes the budget constraint; C_{rt} is for consumption; I_{rt} for investments; EC_{rt} for the energy cost; DC_{rt} for damages and NTX_{rt} for the net trade balance of a region.

$$Y_{\mathrm{rt}} = C_{rt} + I_{rt} + EC_{rt} + DC_{rt} + NTX_{rt} + AR\&D_{rt} \tag{6}$$

We also assume that the two learning technologies could be made available in 2010 if competitive, while their penetration rates are increased (*e.g.*, to 13.5 % *per annum*; *i.e*., above the standard value of 11.5% applied in MERGE). Annualized R&D spending is included in the budget Eq. (6) but they are introduced only when enough benefits are generated to compensate for the cost of research and development. In other words, the induced benefits of the cost reduction for energy production should be greater than the discounted and cumulative cost of R&D. The subsidies option was not active in this study.

3 Case studies

3.1 The BaU cases

Several scenarios related to CO_2 emission control are presented as illustrations of the results generated by this version of MERGE. Apart from the business-as-usual (BaU) cases, where CO_2 emissions are not limited, we have considered the implications of stabilizing atmospheric carbon concentrations to 550-450 ppmv. All scenarios are assessed with and without ETL options. The baseline case is designated by BaUS, where technological change is endogenous. The database for the baseline cases reflects the original technology data of MERGE5, while the growth data are downwards adjusted to reflect the assumptions of the Innovation Modelling Comparison Project (IMCP). Constraints are introduced only on the CO_2 concentration although MERGE considers all other greenhouse gases (GHGs), carbon sinks and aerosols.

All stabilization scenarios without ETL assume that the penetration of backstop technologies is on the same levels as in the baseline case with ETL. This is equivalent with the assumption that in these scenarios the same level of RD&D spending or investments into niche markets will take place.

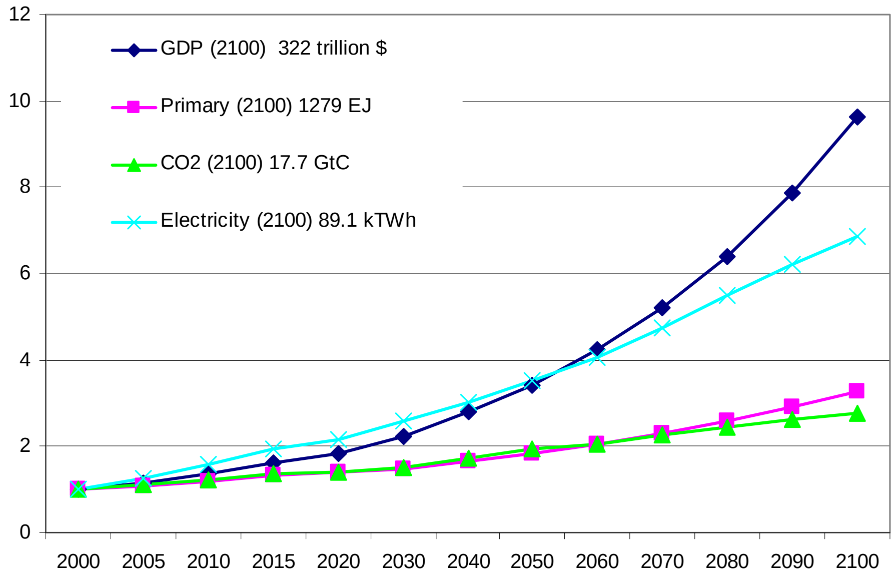

Fig. 1: *Basic indicators for the BaUS case of MERGE with LBD relative to the starting year.*

In the BaUS case, the world GDP grows more than 9 times (*i.e.*, to US$312.5 trillion in 2100); but primary-energy supply and carbon emissions are strongly decoupled from economic growth and increase to 1246 EJ of primary energy per annum (at 45% efficiency for the backstop electricity) and 17.91 GtC/yr carbon emissions in 2100. In the BaUS case, global CO_2 concentrations increase to 693 ppmv, while the average temperature rise between the year 2000 and the year 2100 is 2.36° Celsius. Most of the economic growth occurs in economies (currently) in transition and in developing countries. Regional differences in income, primary-energy intensity, and carbon intensity of GDP are decreasing over time. The currently less-developed countries assume a high economic growth such that they will produce most of the global GDP in the year 2100 while OECD countries will contribute by 38% to the total output. It should be noted that the potential socio-economic growth underlying this scenario is exogenous as well as the autonomous efficiency improvement.

Energy efficiency and decarbonisation continue to contribute to improved energy, economic, and environmental indices. Policies that support technological learning result in a strong contribution of renewables in meeting non-electric-sector demands. This shift enhances the use of non-electric backstop technologies. For the BaUS case, therefore, renewable-energy sources and nuclear contribute 38%, coal 46%, oil 7% and gas 9% of the energy mix. Figure 2 illustrates the impact of learning on the generating cost of electricity for the 450-ppmv cases. We assume a moderate exogenous rate of generation cost reduction that of 0.2% per year. The most significant mechanism in cost reduction is the contribution of the LBD while LBS is important during the first, introductory periods of the new technologies.

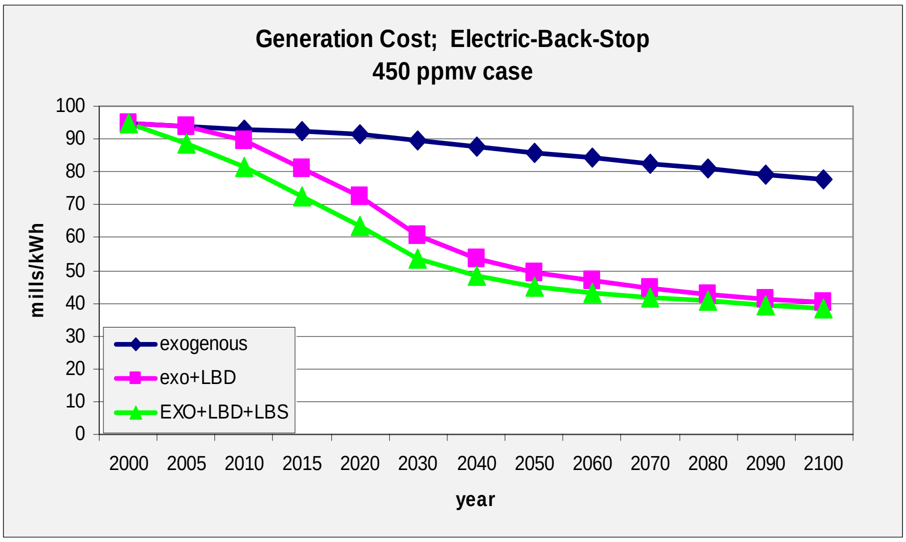

Fig. 2: *A significant cost reduction over time is shown when LBD applies. RD&D policies are important in the early stage of introducing a new technology.*

3.3 Stabilizing carbon concentrations

Economic considerations govern the transition to a low-carbon economy. Two of these considerations represent key options for the second half of this century: the exhaustion of oil and gas resources, and the significant cost reduction in carbon-free energy technologies. When R&D policies are appropriately applied, we attain a significant reduction of energy generation cost and carbon control costs, as shown in Figures 2 to 4. Obviously, the stronger the carbon constraint is, the faster the penetration of carbon-free technologies into the market mixes, and the stronger the relative cost reduction.

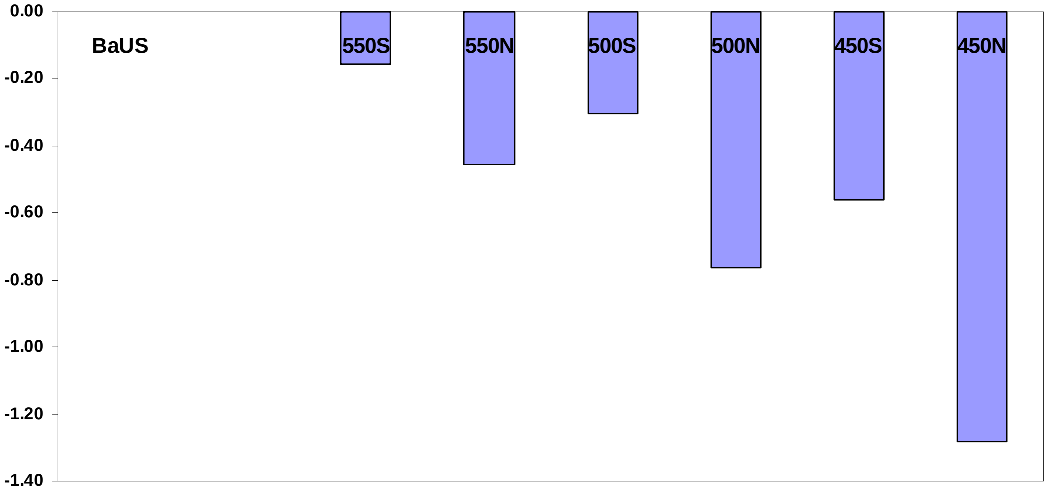

Fig. 3: *Cumulative and undiscounted GWP losses for the Carbon stabilization cases, relative to BaUS. Global losses are significantly reduced in the case of LBD and LBS. For the 450-ppmv cases, the cumulative loss is reduced to 0.56 %.*

The scenarios where atmospheric CO_2 concentration is held to 450-ppmv assume that efficient strategies will be adopted worldwide and a full-scope transfer of “know-how” will take place. Under these circumstances, the following conclusions can be made: First, the induced cumulative GWP losses of the carbon-stabilization are low (e.g., in relation to the cumulative baseline-GWP): for example, below 1.26% in the case without learning, while with ETL policies the GWP losses are less than 0.55% (Figure 3). Secondly, the marginal costs related to carbon stabilization are also reduced to a fraction of the marginal cost without learning (Figure 5), but remain always significant for the case of the 450 ppmv atmospheric carbon limit (e.g., below 600 \$/tC in the 450 ppmv case with ETL).

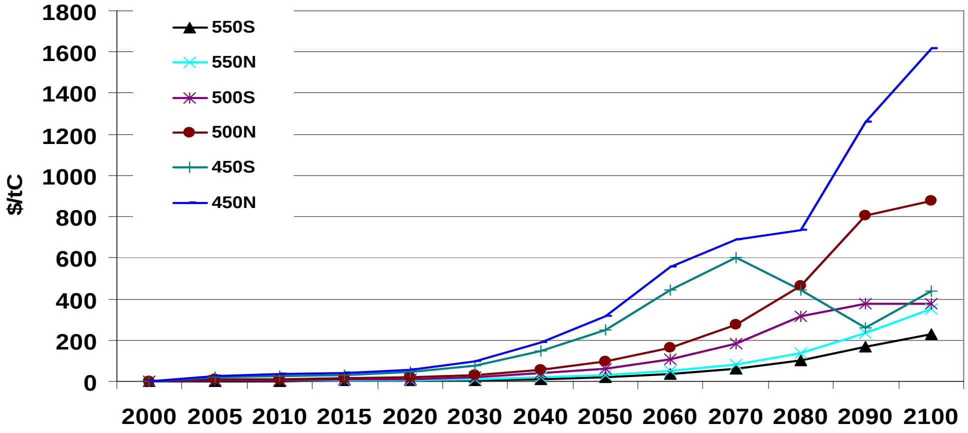

Fig. 4: *The marginal costs of carbon control are reduced by almost 50% by the end of the century in the case of ETL and in relation with cases without learning. To avoid terminal conditions effects on the shadow prices by the end of time horizon the cases have been analyzed up to 2120 while results are reported up to 2100.*

4. Calibration and Sensitivity Analyses

The mathematical formulation of the production function in MERGE is given by the set of equations (7):

$$Y = \left[a\left(K^{\alpha} \cdot L^{(1-\alpha)}\right)^{\rho} + b\left(E^{\beta} \cdot NE^{(1-\beta)}\right)^{\rho} \right]^{1/\rho}$$
$$\text{with } \rho = (\sigma - 1)/\sigma \quad \sigma \neq 0,1,\infty \tag{7}$$

The aggregate economic output Y is described by a nested constant elasticity of substitution function between the value added pairs of capital (K) and Labour (L) and the energy related pairs of electric (E) and non-electric (NE) energy[1]. Details of the calibration procedure are explained in the Appendix together with the key input used for the specification of the reference development.

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[1] MERGE is neither an endogenous growth model nor considers explicitly R&D for the non-energy sector. A new model formulation that includes R&D in energy conservation and non-energy related R&D was beyond the scope of the IMCP study due to time and resource limitations.

The standard MERGE model is calibrated such that the primary energy use, the regional GDP, the installed capacities and electricity production by region are consistent with the statistics of the starting year. Also, emissions and energy flows for the first decades are consistent with EIA projections given in the IEO (2004) report. There is no effort to provide empirical estimates of the production function of the model. Instead, the authors describe in “Buying Greenhouse Gas Insurance” (Manne and Richels, 1992) the model’s ability to reproduce past statistics. This model verification work is not repeated here. Instead, we perform a sensitivity analysis with alternative assumptions on key model input parameters like the elasticity of substitution (ESUB), the autonomous efficiency improvement (AEEI) and the learning rates (LBD & LBS) to check the robustness of our conclusions reported herein and to explain the model behaviour. Details of the sensitivity analyses are explained in the Appendix.

As the model introduces R&D spending as a decision variable, it was not possible to perform any sensitivity analyses on R&D other than assuming different elasticity values for learning by searching. Thus, learning elasticity rates describing LBD and the LBS performance are reduced to 50% of their reference levels.

The AEEI factor is a modelling invention to describe the autonomous (i.e., price independent) decoupling between economic growth and primary energy use. MERGE assumes that the AEEI is a given fraction (e.g., 40% to 50%) of the regional economic growth rate. In most of the cases structural economic changes and not the efficiency improvement, explain the value of the factor, in spite of the name used. On the other hand, the elasticity of substitution (ESUB) describes the price-induced substitution for energy using capital and labour when the energy price changes. The higher the value of ESUB the easier it is to substitute capital and labour for energy when prices increase. Interesting is to emphasize that at low energy system costs ESUB is almost the same as the absolute value of the price elasticity of demand. In the sensitivity analyses ESUB is increased by 10% for Annex I and by 20% for non-Annex I regions. Key results are reported in Figures 5 and 6; e.g., the primary energy use change and the cumulative GWP in relation with the 450 ppmv case under endogenous technological change.

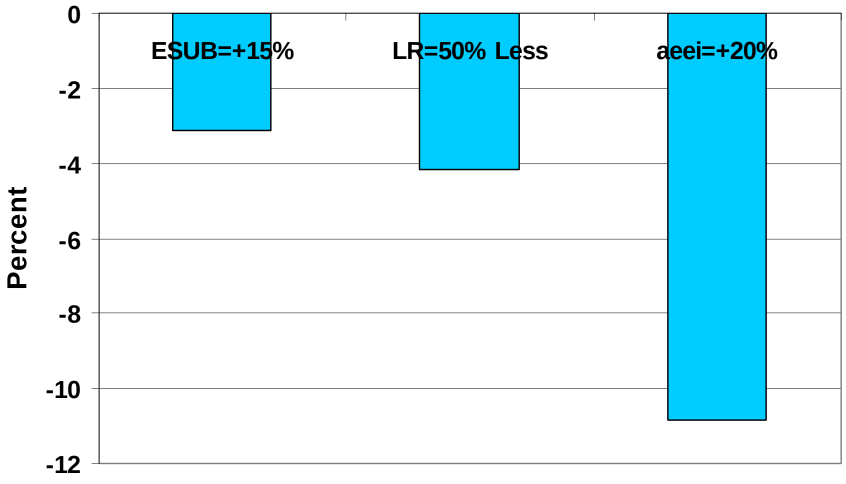

Fig. 5: *Cumulative Primary Energy (2000-2120) change relative to 450 ppmv Reference case in percent. The level of primary energy use per case is very sensitive to the AEEI factor.*

Results on primary energy use are very sensitive to the AEEI factor but less sensitive to ESUB. Assuming a reduction by 50% to the LBD and the LBS elasticity increases the economic cost of carbon control and the marginal cost of energy production and reduces primary energy demand as energy becomes more expensive.

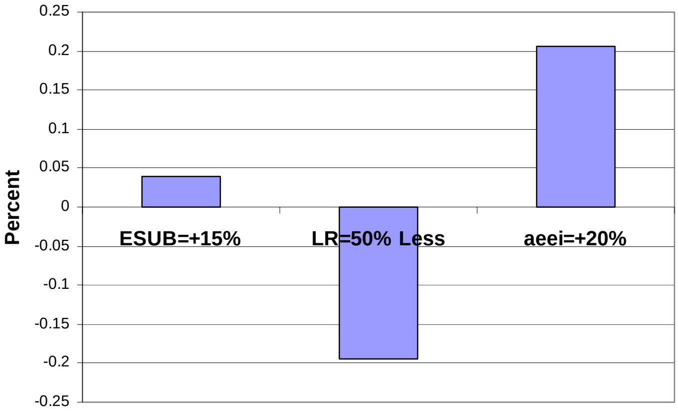

Fig. 6: *Cumulative GWP change (2000-2120) relative to the 450 ppmv reference case in percent*

5. Conclusions

Technological progress has and will continue to play a fundamental role in the evolution of energy systems; as such progress favours the transition toward more-efficient, economic, and cleaner energy technologies, rather than being driven by resource depletion *per se*. It is important, therefore, to incorporate the dynamics of technological change into energy system models. The work reported herein quantifies the impacts of RD&D spending on the development and promotion of carbon-free energy technologies that mitigate global warming. To quantify these impacts, the TFLC formulation has been introduced together with learning investments in favour of the two clusters of backstop technologies in MERGE5. Impacts have been quantified with the help of top-level economy indicators and a sensitivity analyses on key input factors is performed. We also considered several scenarios related to CO_2 emissions and technological learning.

Although our model shows that technological learning favours new advanced back-stop systems, this model formulation does not significantly change the conclusions derived from the original MERGE model for the first half of this century; as fossil fuels (mainly coal and natural gas) will continue to retain a significant share of the global electricity and energy-supply markets in the next 50 years, while energy-related carbon emissions will continue to grow substantially. But, RD&D spending is significantly increased in the first half of the century paving the way to reach carbon mitigation targets.

In the case where atmospheric carbon is stabilized at 450-ppmv, a significant development and market penetration of low-carbon generation options is required. Technological learning in these circumstances favours new advanced systems, represented collectively in the model as electric and non-electric backstop systems. Finally, the importance of technological progress for carbon control has been shown, as such progress allows low-cost carbon-reduction options to enter the generation mix and, hence, reduces GWP losses and minimizes the marginal cost of carbon control.

With the help of the main results and the sensitivity analyses shown herein, we conclude that RD&D increased commitments (either private or public) towards the development of new technologies, is a key strategy against global warming as otherwise conventional technologies will be locked-in the system.

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Appendix: MERGE calibration

The production function

The aggregate economic output Y is described by a nested constant elasticity of substitution function between the value added pairs of capital (K) and Labour (L) and the energy related pairs of electric (E) and non-electric (NE) energy. a and b are scaling factors which are defined based on first-order optimality conditions taking into account the price of oil at the refinery at gate. The autonomous energy efficiency improvement factor (AEEI) is summarized by the growth of the scaling factor b. α denotes the optimal value share of capital in the value added pair and β the optimal value share of electricity in the energy pair.

$$Y = \left[a\left(K^{\alpha} \cdot L^{(1-\alpha)}\right)^{\rho} + b\left(E^{\beta} \cdot NE^{(1-\beta)}\right)^{\rho}\right]^{1/\rho}$$

$$\text{with } \rho = (\sigma - 1)/\sigma \quad \sigma \neq 0,1,\infty$$

$$\text{if } \mathrm{f} \equiv a\left(K^{\alpha} \cdot L^{(1-\alpha)}\right)^{\rho} + b\left(E^{\beta} \cdot NE^{(1-\beta)}\right)^{\rho} \text{ then, } Y = f^{1/\rho}$$

Calibration

We apply the first-order optimality condition for the starting period:

$$\partial Y / \partial NE = PN = \partial Y / \partial f \cdot \partial f / \partial \mathrm{NE}$$

$$PN = 1/\rho \cdot f^{1/\rho - 1} \cdot \rho \cdot b \cdot (1-\beta) \cdot E^{\beta \cdot \rho} \cdot NE^{(1-\beta)\rho - 1} \quad \Rightarrow$$

$$\mathrm{b} = PN \cdot Y^{\rho - 1} / ((1-\beta) \cdot E^{\beta \cdot \rho} \cdot NE^{(1-\beta)\rho - 1})$$

with known b we can define a as:

$$a = Y^{\rho} - b\left(E^{\beta} \cdot NE^{(1-\beta)}\right)^{\rho} / \left(K^{\alpha} \cdot L^{(1-\alpha)}\right)^{\rho}$$

The autonomous energy efficiency improvement factors (aeei):

We assume that energy use per unit of output follows an autonomous (i.e., price independent) annual rate of efficiency improvement $aeei$. The factor is defined such that it varies around 0.5% of the GDP growth rate. The factors and the Labour productivity define the reference energy use time path assuming that energy prices remain constant.

$$Eref_t = L_t \cdot E_0 \cdot \prod_{\tau=1,t} (1 - aeei_{\tau})^{nypp}$$

$$Nref_t = L_t \cdot N_0 \cdot \prod_{\tau=1,t} (1 - aeei_{\tau})^{nypp}$$

$$Yref_t = L_t \cdot Y_0$$

$$Kref_t = L_t \cdot K_0$$

Applying the first-order optimality conditions again we can define the reference development such that the scaling factors depend on time and to avoid the rebound effect i.e., artificial demand increase.

$$b_t = PN_0 \cdot Yref_t^{\rho-1} / ((1-\beta) \cdot Eref_t^{\beta \cdot \rho} \cdot Nref_t^{(1-\beta)\rho-1})$$
$$a_t = Yref_t^{\rho} - b_t \cdot \left(Eref_t^{\beta} \cdot Nref_t^{(1-\beta)}\right)^{\rho} / \left(Kref_t^{\alpha} \cdot L_t^{(1-\alpha)}\right)^{\rho}$$

Data used in the model and values applied in the sensitivity analyses:

Table 1: Regional population in billions

	Usa	**Weur**	**Japan**	**Canz**	**Eefsu**	**china**	**India**	**Mopec**	**Row**
2000	0.276	0.389	0.127	0.054	0.412	1.275	1.009	0.608	1.899
2005	0.29	0.39	0.13	0.06	0.41	1.32	1.09	0.67	2.09
2010	0.30	0.39	0.13	0.06	0.40	1.37	1.16	0.73	2.28
2015	0.31	0.39	0.13	0.06	0.40	1.41	1.23	0.79	2.48
2020	0.33	0.39	0.13	0.06	0.39	1.45	1.29	0.86	2.68
2030	0.33	0.39	0.13	0.06	0.39	1.47	1.36	0.95	2.97
2040	0.33	0.39	0.13	0.06	0.39	1.49	1.41	1.03	3.21
2050	0.325	0.387	0.126	0.063	0.394	1.494	1.442	1.093	3.403
2060	0.325	0.387	0.126	0.063	0.394	1.497	1.462	1.146	3.564
2070	0.325	0.387	0.126	0.063	0.394	1.498	1.475	1.19	3.696
2080	0.325	0.387	0.126	0.063	0.394	1.499	1.484	1.226	3.804
2090	0.325	0.387	0.126	0.063	0.394	1.5	1.489	1.256	3.894
2100	0.325	0.387	0.126	0.063	0.394	1.5	1.493	1.281	3.967
2110	0.325	0.387	0.126	0.063	0.394	1.5	1.496	1.302	4.027
2120	0.33	0.39	0.13	0.06	0.39	1.50	1.50	1.32	4.08

Table 2: Reference development expressed as GDP in trillion USA $2000 per year that defines the labour productivity growth (L)

	Usa	Weur	Japan	Canz	Eefsu	china	India	Mopec	Row
2000	9.83	9.76	4.60	1.32	1.05	1.17	0.52	1.25	3.91
2005	11.08	10.88	4.88	1.54	1.29	1.68	0.67	1.46	4.55
2010	13.10	12.26	5.42	1.79	1.59	2.30	0.87	1.83	5.72
2015	15.273	13.762	5.937	2.057	1.93	3.092	1.129	2.266	7.08
2020	17.584	15.439	6.461	2.353	2.32	4.126	1.457	2.75	8.596
2030	19.735	17.869	7.185	2.752	2.994	5.967	2.227	3.861	12.055
2040	22.026	20.556	7.956	3.198	3.853	8.524	3.33	5.279	16.461
2050	24.439	23.486	8.769	3.689	4.942	12.077	4.909	7.08	22.047
2060	26.951	26.639	9.619	4.221	6.313	16.987	7.164	9.354	29.093
2070	29.534	29.979	10.498	4.789	8.023	23.704	10.37	12.211	37.933
2080	32.154	33.463	11.4	5.384	10.132	32.754	14.891	15.777	48.954
2090	34.779	37.034	12.313	5.997	12.696	44.69	21.199	20.196	62.595
2100	37.375	40.635	13.23	6.615	15.76	59.993	29.863	25.622	79.337
2110	39.908	44.202	14.14	7.227	19.347	78.912	41.51	32.221	99.679
2120	42.35	47.677	15.034	7.822	23.446	101.277	56.72	40.148	124.101

Table 3: Macroeconomic parameters used for the calibration of the production function

	Usa	**Weur**	**Japan**	**Canz**	**Eefsu**	**china**	**India**	**Mopec**	**Row**
Capital to GDP	2.4	2.8	2.8	2.8	3	3	3	3	3
ESUB	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Capital Value-share	0.24	0.28	0.28	0.28	0.3	0.3	0.3	0.3	0.3
Electricity Value-share	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Price of oil $/GJ	4	4	4	4	3.7	4	4	3.7	4
Non-Elect $/GJ	2.75	5	6	4	2.5	2.5	2.5	2.5	2.5

Sensitivity study on the elasticity of substitution (ESUB) by region

	Usa	Weur	Japan	Canz	Eefsu	china	India	Mopec	Row
ESUB-Sensitivity	0.55	0.55	0.55	0.55	0.5	0.5	0.5	0.5	0.5
ESUB-Reference	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4

Sensitivity study on AEEI:

The model defines AEEI by multiplying the annual GDP growth rate (minus of the annual population growth) by a factor of 0.5. This factor was increased by 20%, i.e. from 0.5 to 0.6.

Sensitivity study on learning by doing (LBD) and learning by searching (LBS):

The LBD elasticity was reduced from 20% to 10% per doubling of experience while the LBS factor was reduced from 15% to 7.5% per doubling of knowledge stock.

Results obtained for the sensitivity analyses not shown in the main report:

Two extra figures are given herein; the first refers to cumulative primary energy use and the second to the marginal cost estimates. The primary energy use is quite sensitive to the AEEI factor as it varies almost proportional to the factor modifying the AEEI coefficients. The fact that the relative reduction of the primary energy is not exactly proportional to the change is due to the model specification for the first decades that is kept constant to the results to the International Energy Outlook.

The shadow prices for the 450 ppmv cases indicate the existence of two peaks, one in the year 2070 and a second in the year 2110 with a valley around 2090. It also shows that shadow prices after 2090 are independent of the parameters varied in the sensitivity analyses. The first peak appears only in the 450 ppmv case that forces early and strong penetration of low carbon emitting technologies. The second peak is due to terminal conditions in MERGE.

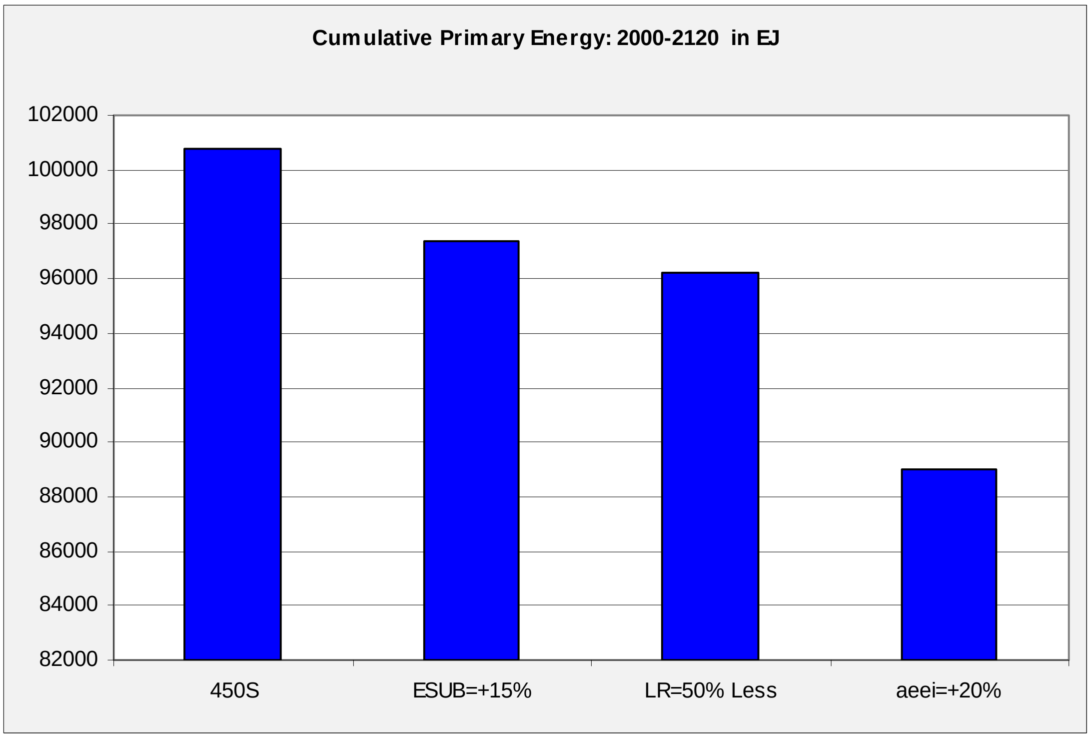

Fig. 7: *Cumulative Primary Energy (2000-2120) for the 450 ppmv reference and sensitivity cases. The primary energy use is very sensitive to the AEEI factor..*

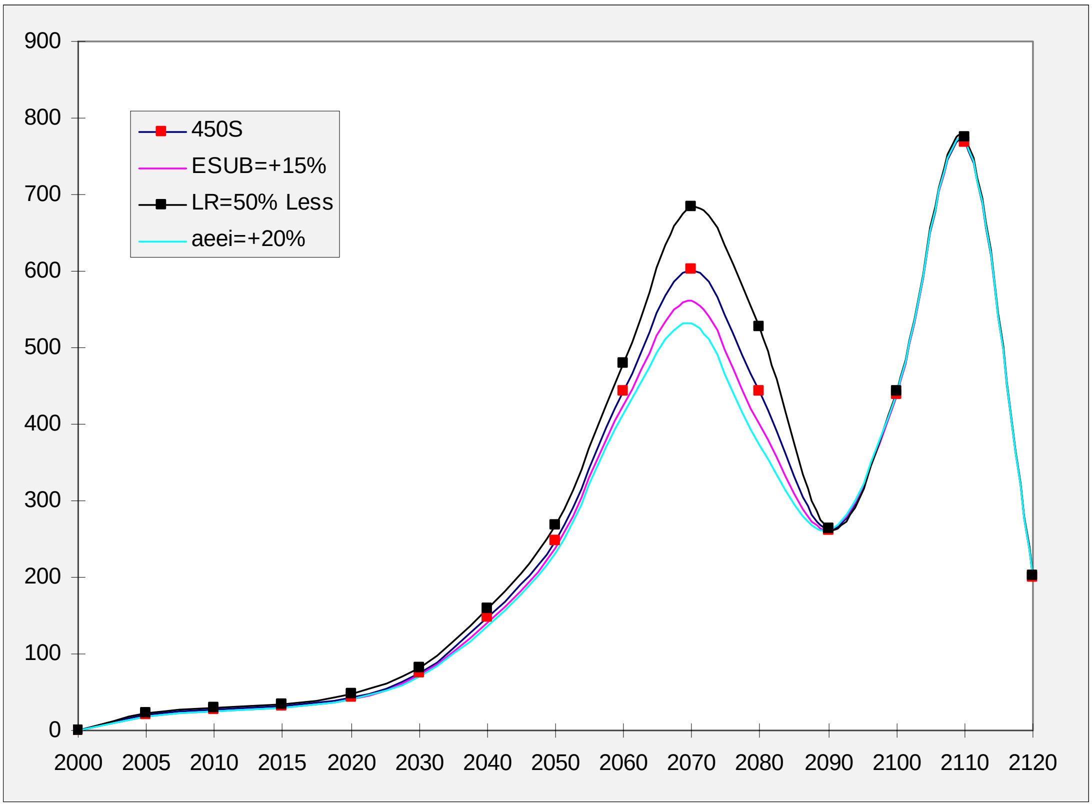

Fig. 8: *Shadow prices for the 450 ppmv reference and sensitivity cases. Model results are sensitive to the reduction of LBD and LBS factors (which are changed by 50%) only around 2070 but back-stop systems do not dictate the shadow prices after 2080.*

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(lxxiv) This paper was presented at the ENGIME Workshop on “Trust and social capital in multicultural cities” Athens, January 19-20, 2004

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(lxxvii) This paper was presented at the Workshop on Infectious Diseases: Ecological and Economic Approaches held in Trieste on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics.

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