Induced Technological Change in a Limited Foresight Optimization Model

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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

The threat of global warming calls for a major transformation of the energy system the coming century. Modeling technological change is an important factor in energy systems modeling. Technological change may be treated as induced by climate policy or as exogenous. We investigate the importance of induced technological change (ITC) in GET-LFL, an iterative optimization model with limited foresight that includes learning-by-doing. Scenarios for stabilization of atmospheric CO2 concentrations at 400, 450, 500 and 550 ppm are studied. We find that the introduction of ITC reduces the total net present value of the abatement cost over this century by 3-9% compared to a case where technological learning is exogenous. Technology specific polices which force the introduction of fuel cell cars and solar PV in combination with ITC reduce the costs further by 4-7% and lead to significantly different technological solutions in different sectors, primarily in the transport sector.

Keywords: Energy system model, Limited foresight, Climate policy, Endougenous learning, Technological lock-in

JEL Classification: O33

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1. Introduction

Anthropogenic emissions of greenhouse gases have raised the annual average global surface temperatures (Houghton et al 2001). The energy system is the single most important source of net carbon dioxide emissions. Thus, in order to prevent further anthropogenically induced climate change, the energy system must be transformed to a system with significantly lower carbon emissions. Energy systems models have been used in order to identify cost-effective carbon abatement strategies, as well as to estimate costs of stabilizing the atmospheric carbon concentration (Azar et al, 2003, Manne & Richels, 1997).

One crucial issue in energy systems models have been how to deal with technological change. Traditionally models have assumed exogenous learning over time for technologies (Azar & Dowlatabadi, 1999). More recent models have, however, started to use learning-curves in order to endogenise technological learning (Mattsson & Wene, 1996; Barreto, 2001; Seebregts et al, 2000). This is particular important for emerging technologies e.g. solar PV, fuel cell and wind. Under such modelling approaches, accumulative installed capacities rather than time itself lead lower costs. Some models have also implemented two-factor learning curves, including also learning from R&D (Bahn and Kypreos, 2002). Endogenous learning in optimisation models, however, causes some computational problems since the optimization problem becomes non-convex. It is for that reason not possible to guarantee a global optimal solution. Therefore Mixed Integer Programming (MIP) is often used, which amounts to a linear approximation of the model. This guarantees global optimality at the expense of increased computation time (Bahn and Kypreos, 2002).

Most energy system models optimize under perfect foresight. Some recent models have started to elaborate with iterative limited foresight (Martinsen, et al 2004, Nyqvist, 2005). These models do not find the optimal energy system from a social planner's perspective, but they are better suited at simulating market behaviour.

In this paper, we use a model called Global Energy Transition – Limited Foresight with Learning (GET-LFL) in which we combine an optimisation approach based on limited foresight and learning-by-doing. This kind of modelling allows the problem to remain convex, and it has a relatively short computation time.

The aim is to compare the effect of introducing induced technological change (ITC) in an energy system model. However, comparing the changes in abatement costs due to ITC is not a well-defined task. Several types of comparisons can be made. One approach would be to compare an ITC model with a model with technology costs fixed at their year 2000 values. Such an approach would result in lower costs for a model with ITC. Another approach would be to compare a model with ITC with a model with exogenous learning, i.e., where the costs of various technologies drop over time. Under this approach is it unclear whether ITC would lead to lower costs or not. For instance, in the case with exogenous learning, one may assume that the cost drops to very low levels and this could imply that the approach with exogenous learning would lead to lower costs to meet the climate target.

In this paper we compare an ITC case with a case without ITC, in which the cost of different technologies are determined by the endogenous learning generated in a baseline scenario (without the carbon constraint).

The aim of the paper is to:

- Investigate the effect of the assumption of induced technological change on abatement strategies, carbon price and abatement costs for scenarios in which the atmospheric concentration of CO_2 is stabilised at 400, 450, 500 and 550 ppm.

- Study the impact of technology specific policies, i.e., policies directed at developing a specific technology (e.g., a subsidy to wind energy).

The paper is structured as follows: in section 2 we describe the model, especially details concerning how learning-by-doing and iterative limited foresight optimization are implemented. In section 3, our results are presented and discussed and in section 4 conclusions are given.

2. Model description

The basic parameter values and structure in the model are based on the GET model (Azar et al, 2003, 2005). GET is a globally aggregated model that has three end-use sectors, electricity, transportation, and heat (which includes low and high temperature heat for the residential, service, agricultural, and industrial sectors). Primary energy supply sources include coal, oil, natural gas, nuclear power, hydro, biomass, wind- and solar energy (that can be converted into heat, electricity and hydrogen). Conversion plants may convert the primary energy supplies into secondary energy carriers (e.g., hydrogen, synthetic fuels, electricity, natural gas for vehicles and gasoline/diesel). The transportation sector is divided into aviation, ships, trains, cars and trucks and considers explicitly the costs for vehicles and fuel infrastructure.

Carbon capture and storage is an abatement technology in the model that can be used on both fossil fuels and biomass. There are efficiency losses as well as increased capital costs for carbon capture technologies, and an additional cost for transport and storage of the captured CO_2. The cost of transporting and storing CO_2 from biomass is assumed to be twice as high due to smaller scale typically associated with carbon capture from biomass (Azar el al, 2005). The total storage capacity is assumed to be 600 Gton C. Nuclear power, another potential abatement technology, is in the scenarios presented here constrained to the present electricity production due to the political controversy surrounding this technology.

In GET-LFL some important features are changed from the original GET model. The most important one is that the model is an iterative limited foresight model, rather than a perfect foresight model (this feature was introduced by Nyqvist, 2005). Further learning-by-doing and end-use demand is elastic. The price elasticity of energy demand in the transportation sector and electricity sector is set to 0.3, whereas the elasticity in the heat sector is assumed to be 0.4. In the model global GDP and energy demand is based on the CPI baseline (Vuuren et al, 2003), whereas fossil fuels reserves are based on Rogner (1997). A discount rate of 5%/year is used through out the period.

2.1 Learning-by-doing

Learning-by-doing is introduced in the model for both the cost of energy capital and vehicles, and the efficiency of conversion technologies. The costs are reduced by the progress rate for every doubling of cumulative installed capacity (Arrow, 1962; Barreto, 2001). In the absence of investments, costs remain constant.

However, we have assumed an exogenous and exponential decline in the cost for fuel cell cars as well as solar PV. In the year 2100 the costs have declined by 60-70%. This cost development is a proxy for further research and development that we assume will take place regardless of whether there is any climate policy in place or not.

There are great uncertainties about future learning rates for technologies. In this paper we base our estimates of learning rates on (Riahi, 2004; McDonald and

Schrattenholzer, 2001; Kram el al, 2002). We assume the progress rates to be around 5% for mature technologies, such as power production from fossil fuels, and between 10% and 15% for more immature technologies such as carbon capture, wind power, fuel cells and solar PV. Each technology is assumed to have an initial investment cost in the year 2000, and a floor investment cost below which the cost cannot drop. The ratio between the initial and floor investment costs depends on technology, it is around 0.8 for semi-mature technologies such as combined heat and power plants, and around 0.2 for immature technologies such as solar PV.

Further, technological clusters are included in the model in order to model spillover of learning between different technologies, which may give rise to for instance co-evolution of technologies. Five different clusters are included: gasification of biomass and coal (used for production of hydrogen, synthetic fuels as well as electricity), carbon capture technologies that may be used with fossil fuels and biomass in combination with electricity or hydrogen production, synthetic fuels production from biomass, coal and gas, hydrogen production from fossil fuels and biomass, and finally, combined heat and power production. Learning is assumed to partially diffuse between different technologies within the clusters. This is simulated through spillover factors, a factor of 0.5 means that investing 1 kW in say coal gasification leads to the same drop in the cost of biomass gasification (per kW) as investing 0.5 kW in biomass gasification. Spillover factors are set to 0.5 between different fuels (e.g. spill-over from coal gasification to biomass gasification), and 0.8 for the same cluster using the same fuel but for different kinds of production (e.g. carbon capture from hydrogen production to carbon capture from electricity production).

2.2 Limited foresight

GET-LFE is based on iterative optimization with limited foresight, (for details see Nyqvist, 2005). Each time period, t, the model maximises the sum of consumer's and producer's surplus for the next thirty years (when energy demand is fixed the model minimises future energy systems costs). The costs for the different technologies are static, i.e., equal to the cost level in the beginning of the period. The decisions for the first period t are then saved. The next time period, t+1, a new optimization is made thirty years ahead. In this period, the costs of different technologies have probably dropped because of learning by doing in previous period.

The model does not foresee potential cost reductions due to learning the coming periods, neither are scarcity rents generated for the whole period, as they are in perfect foresight models. In GET-LFL scarcity rents on fossil fuels only arise if the "planned" extraction pathway would lead to depletion of the limited resource over the next 30 years.

The model aims to simulate a market with complete spillover of know-how between companies and with a long-term emission target set from policy makers. In this setting companies would not invest in immature more expensive technologies since in a perfect market (according to standard theory) investments are made according to the marginal costs of production. And the full spillover of learning between companies implies that there are no benefits of investing in a more expensive technology in order to reduce costs in the future. However, companies in the real world may foresee some cost reductions, and therefore invest in technologies even though they are not presently profitable. Thus, these interactions are much more complex than modelled here (see e.g. Grubler, 1999).

Further our model is not detailed enough to consider niche markets, e.g., PV may already at present be cost-effective in certain off grid applications (pocket calculators, in space, far from the electricity grid, etc). Such niche markets offer the potential for learning by doing, and there might thus be more learning in the real world than what our model suggests even in the baseline scenario.

2.3 Scenarios and cases

For each stabilization scenario the emissions are bound to a trajectory resulting in an atmospheric concentration of 400, 450, 500 and 550 ppm CO_2 by the year 2100. The emission trajectories, shown in Figure 1, do not allow overshoots, except for the 400 ppm scenario (where the atmospheric concentration peaks in 2060 at 415 ppm). The emissions due to land use changes are also exogenously set using a combination of data from the CPI baseline (Vuuren et al, 2003) and the B2 SRES scenario (Nakicenovic, 2000).

The baseline scenario, without any carbon constraint, is run with endogenous learning. Thereafter, all stabilization scenarios are run in two different ways, one with Induced Technological Change (ITC) and one without Induced Technological Change (no-ITC). The investment costs in the no-ITC case are fixed to follow the cost profiles generated in the baseline scenario. In the ITC case, the emission cap induces investments (in abatement technologies), which causes cost reductions through learning-by-doing.

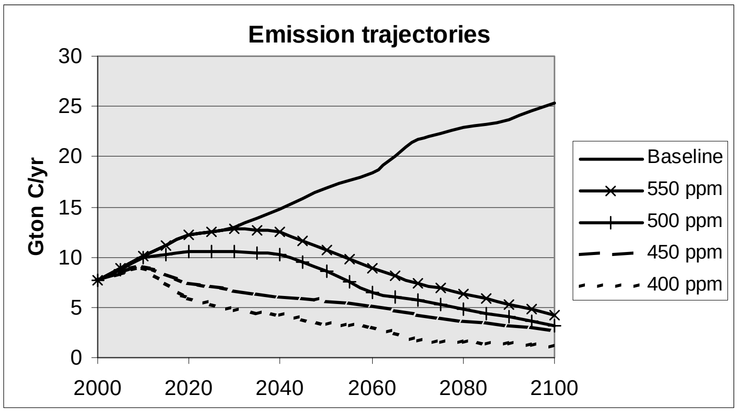

Figure 1. Exogenously set emissions trajectories for each stabilization scenario. The baseline trajectory is generated in a model run without carbon constraint.

3. Result

3.1 The baseline scenario vs. ITC stabilization scenarios

The main abatement option used in all stabilization scenarios are biomass, wind, oil and natural gas instead of coal, a reduction of the energy demand and carbon capture and storage from both coal and biomass (see figure 2). In the baseline scenario (no carbon abatement), oil-based fuels are replaced by synthetic fuels produced from coal around 2050, whereas oil-based fuels are used in the transport sector during an even longer time period in the stabilization scenario. This latter, rather paradoxical result, can be explained by the fact that the costs of synthetic fuels from coal is lower than gasoline from non-conventional oil, whereas the opposite holds for a world with sufficiently high carbon taxes.

More stringent carbon constraints generate higher energy prices which reduce energy demand. The demand is reduced by 30-35% from 2060 and onwards in all scenarios. The reason for the small difference in energy use between the different scenarios is

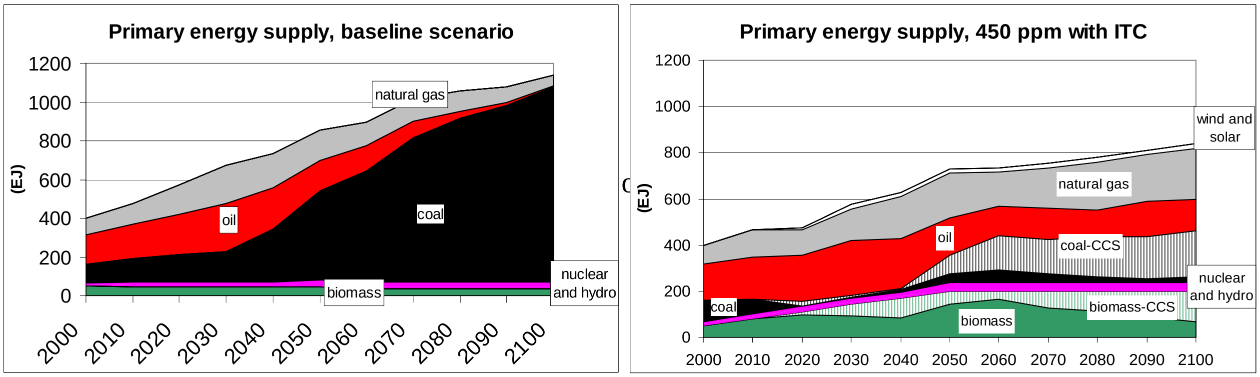

Figure 2a Figure 2b

Figure 2. The primary energy supply in the baseline scenario (2a) and in the 450 ppm stabilization scenario with ITC (2b).

3.2 Comparing ITC and no-ITC cases

Here, we compare the stabilization scenarios with ITC and without ITC (no-ITC). The deviation between the ITC and no-ITC cases for different energy sources is typical less than 5% in all scenarios. However, larger deviations occur for short periods of time for certain energy suppliers, up to 15% in the 500 and 550 ppm scenarios, and up to 20% in the 400 and 450 ppm scenarios.

In the 400 and 450 ppm scenario the ITC case mainly affect the marginal costs of carbon after 2070. In the 450 ppm scenarios the difference between the marginal carbon cost in the ITC case and the no-ITC is around 100 USD/ton C, as seen in figure 3, and around 200-300 USD/ton C for the 400 ppm scenario. The cut in the marginal cost curve in 2090 is due to that the emission trajectory is levelling out in 2090, and then again becomes slightly steeper. In the 500 and 550 ppm scenario, there is a difference of around 100 USD/ton between the ITC and no-ITC cases for both scenarios from 2080 and onwards.

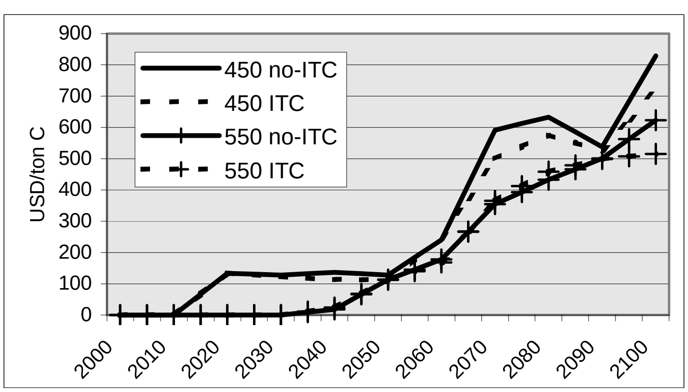

Figure 3 Carbon price in the 450 and 550 ppm scenario, with ITC and without ITC.

The aggregated discounted welfare (sum of consumer's and producer's surplus) loss due to carbon abatement ranges from 10 TUSD in the 400 ppm scenario to 2 TUSD in the 550 ppm scenario. The welfare benefit of ITC compared to no-ITC lies in the range of 3-9% depending on scenario.

3.3 Explanation of the low impact of ITC

There are two main explanations for the small differences between the ITC and the no-ITC cases, these are (*i*) spill-over of knowledge between technologies and (*ii*) large potential of fossil fuel abatement technologies.

First, there is spillover within technological clusters. Therefore, investments in, for instance, gasification of coal, leads to learning that is useful when biomass is gasified (a process that is also of importance for carbon capture). In the baseline scenario, fossil fuels dominate the energy supply. This leads to improvements of technologies that use fossil fuels, and as a result of spill-over of learning, there is also some improvement of biomass and fossil fuel with carbon capture and storage in the baseline scenario.

Second, in the mitigation scenarios, natural gas instead of coal, biomass and carbon capture and storage from fossil fuels and biomass dominate the changes in the energy supply. These technologies are the same technologies that gain learning also in the baseline scenario. More advanced technologies such as fuel cell technologies and hydrogen production from solar, which do not gain learning in the baseline scenario, are not even used in the 400 ppm stabilization scenario until after the year 2100. These two observations explain why the impact of ITC on the welfare cost of carbon abatement is modest (in our modelling approach in the base case runs).

3.4 ITC and technology specific policies

In the previous experiment an emission cap induced investments in the energy system and thereby learning. However, in the real world, investments in more advanced technologies are not only triggered by carbon abatement policies, but also by government policies that support specific technologies. For instance, few expect that private companies will make investments in grid-connected PV only as a result of expectations that there will be a stringent climate policy in place by the year 2030. We here study a case (ITC tech) where technological change is induced by the emission cap as well as of technology specific policies. We define technology specific polices as policies that are primarily aimed at supporting the commercialisation of immature but promising technologies. Such policies include e.g. feed-in tariffs, green certificate and directed subsidies etc.

We prescribe that at least 0.2% (200,000 cars) of the total car stock in 2040 consists of hydrogen fuel cell cars and as many natural gas cars with internal combustion engine in the year 2040. We also prescribe that 0.2% (40 GW_p installed capacity) of the global electricity demand is supplied by solar PV. After 2040, there is no prescribed level for any of these technologies.

By forcing the technologies to enter the market, the costs for these individual technologies are reduced by roughly 60% in only a decade. The impact of technology specific policies is largest in the transport sector, where hydrogen powered fuel cell cars take a significant market share from 2060 and onward in the 400 and 450 ppm scenarios. Also solar PV enters the market in all scenarios, but wind and solar PV together never exceed the limit of 30% of the electricity demand due to the intermittent nature of solar and wind power. Hydrogen production from solar is not a cost-effective option in our scenarios until after the year 2100.

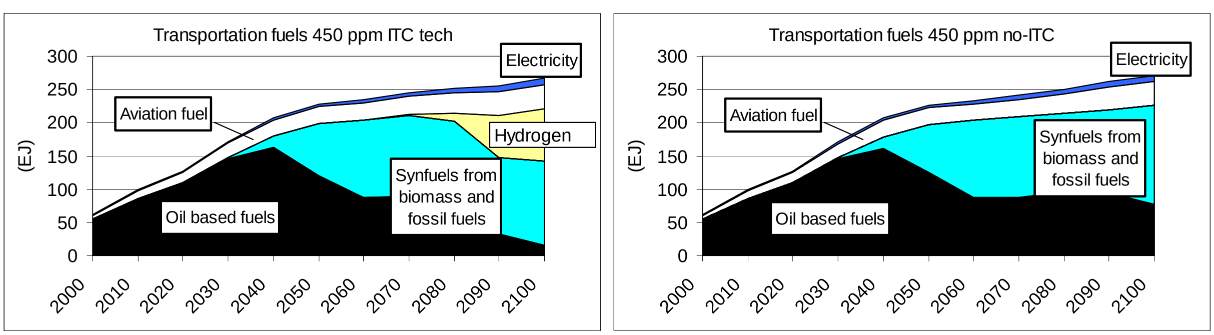

Figure 5a. Figure 5b

Figure 5. Transportation fuels in the 450 ppm scenario in the case with ITC and technology specific policies (ITC tech) (5a) and without ITC (no-ITC)(5b).

The marginal cost of carbon is reduced significantly in the technology specific policy case. The carbon price in the 400 ppm scenario ITC tech case is around 900 USD lower than in the no-ITC case in 2100 (a reduction by 80%). In the 450 ppm scenario the difference is 300-400 USD/ton C as seen in figure 6, whereas 550 ppm scenarios remain fairly unaffected. It is, however, worth noting that the difference in carbon prices is small until 2070, even though the policy is introduced in 2040. This stems from the fact that the advanced technologies are not cost-effective until around 2070 despite their rapid learning rates.

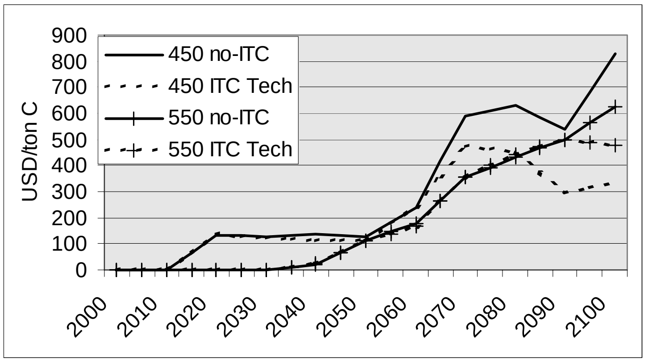

Figure 6. Carbon price of carbon in the 450 and 550 ppm scenario, in the no-ITC and ITC tech cases.

Technology specific policies reduce the costs of carbon abatement compared to both the ITC and no-ITC cases in all scenarios. The reduction of welfare losses ranges from 6 to 16% depending on scenario, see table 1. Since the changes between all cases mainly occur after 2070, the benefit in welfare is discounted to a large extent, which partly explains the fairly small differences in abatement costs.

This modelling exercise also demonstrates the risk for technology lock-in in models with endogenous learning and limited foresight. In the absence of perfect foresight (as is the case in reality!), the market will pick the technologies that happen to be the most competitive without considering the fact that certain technologies can be expected to improve much faster than others, but only if they are given sufficiently large markets which enable learning by doing.

Table 1. Abatement welfare loss in the ITC and ITC with technology policy relative to the without ITC case

	Abatement cost	Cost relative to no-ITC	
	no-ITC (TUSD)	**ITC** (%)	**ITC tech** (%)
400 ppm	9.7	93	84
450 ppm	5.4	91	88
500 ppm	2.7	97	94
550 ppm	1.8	97	93

3.5 Sensitivity analysis

The abatement technologies chosen in the stabilization scenarios as well as total abatement costs are dependent on various choices of parameters. However, for most parameters the relative difference between the ITC and no-ITC case remain fairly constant. In this section we elaborate with parameters that tend to increase the relative importance of ITC.

Assuming that the gas reserves are halved compared to the base case runs, that the availability of carbon storage sites is halved and disregarding spillover within technological clusters, ITC reduces the total abatement cost by around 15% compared to the no-ITC case for all stabilization scenarios. This confirms the argument put forward in section 3.3.

The floor costs set a limit on how much the costs for a specific technology may decrease due to learning. Therefore, even though there are more extensive investments in abatement technologies in the stabilization scenarios, there is a rather small difference in costs for many important abatement technologies between the ITC case and the baseline (and thereby the no-ITC case as well). Assuming that the costs of technologies may decrease below the floor costs therefore increase the effect of ITC. The total abatement cost is reduced by 15-20% in the ITC case compared to the no-ITC case for the 400 and 450 ppm scenarios. The difference is even larger for the 500 and 550 ppm scenarios, around 30-35%.

Still, even if the total abatement cost may be sensitive for some parameters, the mitigation strategy is not. The primary energy supply does not alter significantly between the ITC and no-ITC cases in the sensitivity analysis. What may cause major changes in the energy system is technology specific polices.

4 Conclusion and discussion

We have analysed the impact of introducing induced technological change in an energy systems model called GET-LFL, which is an optimization model with limited foresight.

Our main results may be summarized as

- The introduction of induced technological change (ITC) leads to a reduction of the overall cost to meet the climate target by 3-9% compared to a case without ITC (no-ITC).

- The introduction of ITC does not lead to any major changes in the energy supply in our model compared to our case without ITC (in general the difference in the energy supply mix remain below 5%).

- ITC in combination with technology specific policies alters the transport energy supply system significantly in the 400 and 450 ppm scenarios after 2070, and reduces the total abatement cost by 12-16% compared to the no-ITC cases.

It is important to note that the cost reductions reported above depend heavily on assumptions that were made for the no ITC scenario. Thus, our results should not be interpreted as if technological change is not particularly important to meet stringent climate targets. Clearly, a radical transformation of the energy system is needed if we are to achieve perhaps a 90% reduction in emissions compared to baseline by the end of the century.

The key reason why ITC does not seem to play an important role in reducing costs to meet the climate targets in this paper is that there is quite some learning in the base case and the assumption that this learning reduces the abatement cost in the no-ITC case.

This way of defining the technological development in the no-ITC case is just one out of many ways. An alternative way would have been to make comparisons with a scenario without any technological development at all. Under such an assumption, ITC would have emerged from the modelling exercise as extremely important. It may not even be possible to reach a 450 ppm scenario with currently existing technologies Alternatively, one could have compared the ITC case with a case with exogenous rapid learning. In this case, ITC could have turned out to be more costly.

One of the more important insights demonstrated in our modelling approach is that endogenous learning may lead to path dependencies. Such phenomena are difficult to obtain in models with perfect foresight. We show that by introducing technology specific policies in the form of a forced introduction of fuel cells and solar PV. This turns out to quite radically alter the transport sector. The reason for this is that the mandatory use of fuel cell reduces the cost of this technology so that it becomes the most cost-effective option in the transport sector. Thus without technology specific polices the energy system is locked into a cost ineffective state. This highlights the importance of not only relying on general price instruments when developing climate policies. Rather, technology specific polices, such as subsidies, green certificates and feed-in tariffs, therefore seem to be an important complement to higher carbon prices (Sandén and Azar, 2005)

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(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

(lxxi) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

(lxxii) This paper was presented at the 10th Coalition Theory Network Workshop held in Paris, France on 28-29 January 2005 and organised by EUREQua.

(lxxiii) This paper was presented at the 2nd Workshop on "Inclusive Wealth and Accounting Prices" held in Trieste, Italy 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

(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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