

Technology evolution and energy modelling: overview of research and findings

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Abstract: This paper provides an overview of the research work carried out within the TEEM research project regarding technology progress and the endogenous representation in energy modelling. It also provides an overview of the model applications that aimed at improving policy-oriented understanding of climate change mitigation when endogenous technology progress is considered. Finally, the paper draws general conclusions for energy and environment policy, energy technology and energy modelling techniques.

Keywords: Energy modelling; climate change; energy technology; endogenous technology progress; TEEM project.

1. Preface

This paper draws extensively on the TEEM project (for a full reference see also Capros, 2000) that was carried out in 1998 and 1999 by a consortium of European organisations and was partly funded by the European Commission's 4th Framework Research Programme, Directorate General of Research. The organisations which have contributed to this research were: Institute of Computers and Communication Systems of National Technical University of Athens (ICCS/NTUA, Greece), who were the project coordinators; Netherlands Energy Research Foundation, Unit Policy Studies (ECN, the Netherlands); Institut d' Economie et de Politique de l' Energie (IEPE, France); Paul Scherrer Institut, Department of General Energy Research (PSI, Switzerland); Energy for Sustainable Development Ltd (ESD, UK); Institute of Economics and the Rational Use of Energy, University of Stuttgart (IER, Germany); International Institute for Applied Systems Analysis, Environmentally Compatible Energy Strategies (IIASA, Austria); European Commission, Joint Research Centre, Institute for Prospective technological Studies (IPTS/JRC, Spain); Katholieke Universiteit Leuven, Centre for Economic Studies (CES/KUL, Belgium); with further contributions from: ECOSIM Cons. Ltd (UK), Maastricht Economic Research Institute on Innovation and Technology (MERIT, the Netherlands), Centre for Renewable Energy Sources (CRES, Greece), Mr. L. Vouyoukas (independent consultant, Greece).

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2. Introduction

Technological change, also referred to as technological progress, is widely recognised as a key factor in economic progress as it enhances the productivity of factor inputs. It is generally accepted that the improvement of technology induces benefits for the economy and that, consequently, Research and Development (R&D) programmes and policies are important for economic growth (for a recent overview of the relevant economic theory, see Aghion and Howitt, 1998).

There are also many historical examples where policies or, more generally, overall economic and societal objectives can accelerate the rate of technological improvement. For energy technologies in particular, it is widely accepted that technology progress has been influenced by events and policies such as the oil price shocks, the renewable programmes, acid rain concerns and the prospects of large exports of power equipment.

In recent years it has been argued that targeted technological development could serve as major means to reconcile economic ambitions with environmental considerations. This raises the issue that assessments of future trajectories of, for example, energy systems should take

into account context-specific technological progress. Rather than taking the characteristics of existing and emerging technologies as a given, their development should be a function of the dedicated R&D funding and the anticipated market penetration and deployment of the technology under the prevailing economic context. If this relationship between policy objectives and technological progress is proven to be true then the policy implications are considerable: the costs of complying with climate change imperatives could then be much lower than naively expected, since induced technology progress would lower these costs.

Energy systems analysis and models have mostly neglected this causal relationship. This omission has arisen first because of limited empirical understanding of the drivers of technological change and second because of inherent difficulties in the modelling of energy and economic systems with induced technological change. However, recent research in energy systems analysis provides evidence of an effective empirical approach to this problem. The corresponding analysis shows that energy and environmental (in particular for global warming) strategies have to be substantially re-considered if evaluated in the presence of an induced technology progress relationship.

Typically, energy scenarios analysed with energy system models assume that characteristics of technologies can change over time. This can be seen as a reflection of technology dynamics (learning). However, the trend is often assumed to be exogenous – a function of time, for instance – a given parameter for the energy system analysis model. This applies to technology cost indicators like the specific investment cost and to performance indicators, like the thermal efficiency of energy technologies.

Endogenous technological learning has been recently shown to be a very promising new feature in energy system models. A learning curve, or experience curve, describes the specific cost (for example the cost when investing one unit) as a function of the cumulative installed capacity of a given technology. It reflects the fact that technologies may experience declining costs as a result of their increasing adoption in the economy. Such a negative correlation between the cost of a unit and the cumulative penetration of a technology has been empirically verified and observed. Such a relationship may reflect the effects of many factors, such as accumulation of knowledge, economies of scale, standardisation, etc. that are also shortly described as processes of learning by doing and learning by using (or learning by experience).

Pioneering energy modelling work has been carried out in this field by the models GENIE (Mattsson 1997, Mattsson 1998) and MESSAGE (Messner, 1997). They have shown that formulations with endogenous learning are feasible and lead to insights not directly obtainable from conventional models. These two models apply the learning mechanism to the specific capital cost of energy production technologies and adopt a learning or experience curve

approach: the specific capital cost of a ‘learning’ technology decreases as a function of cumulative capacity (‘learning by doing’ mechanism).

The research project ‘Energy Technology Dynamics and Advanced Energy System Modelling’ (TEEM) started from this pioneering experience (Messner, 1998) and generalised the approach both in size (larger models and enhancement of policy analysis) and in scope (more learning techniques and also implementation on energy market models and on global optimisation ones). The project carried out a comprehensive application of the enhanced models to study the role of energy technology and their dynamics as induced by policy aiming at reducing energy-related carbon dioxide emissions in Europe and Worldwide. In modelling terms the research focused on the representation of energy technology progress as an endogenous process within energy system models.

A challenging objective of TEEM was to assist in the appraisal of costs and benefits of technology development in order to evaluate the expected benefits from R&D policy success in the energy field. Research in this field is a novel task in the sense that it challenges the state-of-the-art of analysis. Hence, only tentative answers to quantitative questions about the effectiveness of R&D expenditures – and thereby about the economic benefits of their results – seem possible at this stage.

In the domain of research in modelling techniques, the TEEM project examined the difficulties and the various approaches available for the endogenisation of technology dynamics in energy models (e.g., learning by doing and using) and in the inclusion of stochastic and hedging aspects of the issue. In view of the overall context of the project, these analytical innovations have been applied to the selection and improved timing of greenhouse gas mitigation measures in the context of the European Union.

The TEEM project specified and developed models that include endogenous energy technology evolution mechanisms that are rooted in recent advancements in industrial economics. Technology progress is specified in a way that represents the dynamic effects of R&D policy, including innovation funding, appropriability conditions, international co-operation and diffusion of technologies. The impact of related issues, such as learning by doing, learning from experience, economies of scale, capital stock turnover, hedging strategies etc., was also examined.

3. Methodology

Overview

The threat of adverse climate change and the implications on the energy system is the policy issue that drives the research presented here. A major characteristic of this problem is the high

uncertainty surrounding the potential damages of future climate change, which according to prevailing scientific indications could be very significant.

Methodologically, this situation of high uncertainty combined with high potential impacts is strikingly similar to the economics of R&D, which is also characterised by potentially significant consequences (in this case, benefits) and high uncertainties at the same time. In both cases a full quantification remains a challenging and unfinished task. Thus, the expected impact of the research presented here is of exactly the same nature as that of its two constituent problem areas, climate change and R&D benefits: potentially very important, but quantifiable only at a limited degree of accuracy.

In order to meet the objective of the endogenisation of technology progress, it was necessary to develop state of art modelling of a) energy and climate change and b) technology dynamics.

It has been evident that the assumptions concerning the evolution of future technologies affect considerably the results of most models, including the models used in this research. Thus, the project focused on the development, among others, of a) a typology of energy technologies and their dynamic characteristics, and b) a consistent methodological framework for incorporating technology dynamics and their links to public policy in large-scale energy models.

In view of the analytical complexity of the endogenisation of technological progress and the exploratory nature of the work in this area, multiple models have been used for the purposes of the project. For example, full endogenisation even with simplistic assumptions is not viable yet for some large-scale energy models. Thus, a number of results are based on purpose built models that seek to analyse at a highly aggregated level some of the issues involved in the endogenisation of technology and the nature of technological expectations.

Despite the progress of the research reported here, a number of methodological, informational and other difficulties remain in the analysis. These include lack of theoretical rigour in some key areas of induced technological progress, weaknesses in R&D data, difficulties in measuring and evaluating technological development etc.

Models used

In order to meet the objectives stated above, the TEEM project involved many major European energy modelling teams, including PRIMES (ICCS/NTUA and KUL), POLES (IEPE, ECOSIM and IPTS), MARKAL (ECN, PSI, and KUL) and MESSAGE (IIASA). These models follow different methodologies and rely on a variety of background experiences. A research objective of TEEM was to harmonise and consolidate a common methodology in order to make technology dynamics endogenous within the above models. For this purpose, apart from workshops and methodological notes, a common prototype

model was developed called ERIS. Also, for harmonisation and consistency purposes, the project ensured that all modelling teams used the same assumptions, especially regarding the technical-economic parameters and dynamic relationships of energy technologies. For this purpose, research, collection of data and estimates were gathered under a common database structure called E3TDB.

A short description of the models used is given below.

ERIS (Energy Research and Investment Strategy) is a global energy model prototype specified and developed in the context of the TEEM project (Kypreos *et al*, 2000). The original purpose of ERIS was to capture the main mechanisms regarding the endogenous analysis of technological learning under uncertainty and to allow for a consistent cost-benefit analysis of specific policies aiming at technology prioritisation. The original prototype specified by IIASA and coded by NTUA considered a non-linear programming (NLP) and a Mixed Complementarity (MC) formulation of experience curves. ERIS was extended by PSI to include more general constraints, a stochastic approach and a Mixed Integer Programming (MIP) formulation of learning curves.

MESSAGE is a dynamic linear programming model that is specifically suited for complex, multi-regional models (Messner and Schrattenholzer, 1998). It has been developed at the International Institute for Applied Systems Analysis (IIASA). The model is typically used in long-term scientific investigations (see, e.g., IIASA-WEC, 1998), but also in analyses for specific planning issues. MESSAGE exists in many versions, including one that has endogenous non-linear learning curves and one that accounts for uncertainties. All versions can be classified as being a bottom-up technology-oriented model, requiring the provision of energy-related demands as inputs.

MARKAL is a widely applied bottom-up, dynamic linear programming (LP) model developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). Besides the 'standard' MARKAL LP model, which has provisions to model material flows within the energy system and to include uncertainty by a stochastic programming approach, the MARKAL family of models includes the MARKAL-MACRO model (a relatively new (NLP) model that combines the technological detail of standard MARKAL with the general economics of MACRO, a long-term neoclassical growth model), and the MARKAL-MICRO (NLP) and MARKAL-ED (LP) models, which have a partial equilibrium model not representing the rest of the economic system, but allowing demands to be reduced in response to higher energy prices. With only a few exceptions, the individual capabilities of the model are additive in nature, that is they can be used in combination with each other and are embedded in a single software system. Experience from MARKAL models with endogenous learning was gained for a small-scale example, a simple

global MARKAL model and for a large-scale example covering Western Europe (Seebregts *et al*, 1998).

The PRIMES energy model was designed in 1993-4 and focuses on market-related mechanisms influencing the evolution of energy demand and supply and the context for technology penetration in the market. The PRIMES model also was designed to serve as an energy policy analysis tool and includes the relationships between energy policy and technology assessment. The need to represent the growing process of market liberalisation motivated PRIMES to adopt a market-oriented modelling approach. The current version of the model (version 2) formulated as a non-linear mixed complementarity (MCP) problem and solved under GAMS/CPLEX/PATH is fully operational and calibrated on 1995 data for all European Union member states (Capros and Mantzos, 1999). The model application for the European Union is very detailed and comprehensive, covering a large number of energy demand and supply sectors and markets. The model produces long and medium term projections of energy balances, investment, costs, prices and technology choice.

The POLES model is a sectoral model of the world energy system. It has been developed in the framework of a hierarchical structure of interconnected sub-models at the international, regional and national level. The dynamics of the model is based on a recursive (year by year) simulation process of energy demand and supply with lagged adjustments to prices and a feedback loop through international energy prices. Since 1997 the model is operational and can produce detailed long term (2030) world energy and CO₂ emission outlooks with demand, supply and price projections by main region (Criqui and Kouvaritakis, 1997).

4. The history and theory of technology dynamics

Scope of research work

The foundations of the economic theory of technological change go back to late 20s and early 30s and refer to fundamental concepts developed independently by Usher, Hicks and Schumpeter. In the 50s the research field gained renewed attention within the neoclassical growth theory, first influenced by the work of Solow and then reflected in the work of Arrow. After more than 30 years, new research interest on the drivers of economic growth gave rise to the so-called “endogenous growth theory” reflected in the work of Romer, Barro, Lucas and others.

The research approach of TEEM project uses endogenous growth concepts and attempts their empirical application in the context of energy systems models. The empirical approach starts from an historical analysis of three main waves of technological change that profoundly altered the energy sector over the past thirty years and the key factors that were responsible for these changes. Emphasis is put on two of the most important such factors, namely, public

research and development spending and learning rates for which statistical data and time series have been collected.

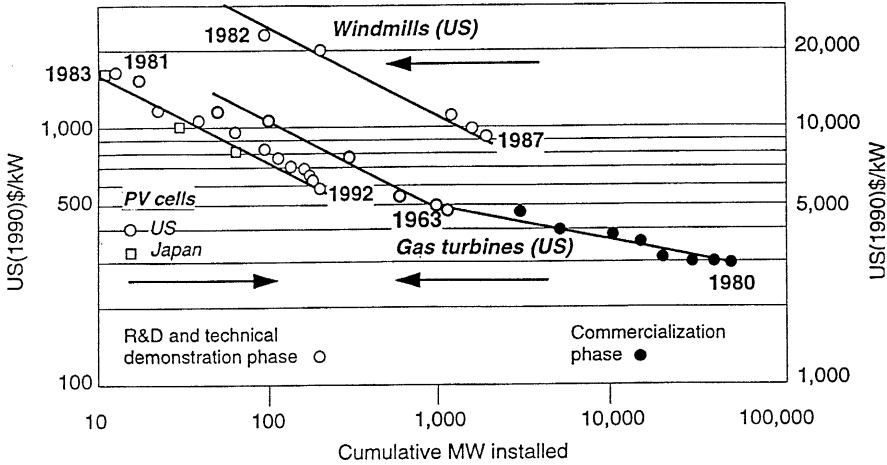


FIGURE 1. *Historical examples of learning curves relating capital costs to cumulative installed capacity.*

The main conceptual and empirical construct used in the TEEM project is the learning-by-doing curve. This curve shows a reduction of capital costs (cost of purchasing one more unit of a technology to make a new investment) of a technology as the number of cumulative installations increase. Such a curve summarises a variety of mechanisms, including learning in innovation, progress along the various stages of R&D as market prospects increase, accumulation of experience and economies of scale. Historical observations do confirm such a relationship. Figure 1 shows such historical information for a set of energy technologies. Within TEEM, work was devoted on the econometric estimation of learning by doing curves for selected new energy technologies. Data were collected for this purpose. The learning rates resulting from the econometric estimations have been used in all model applications.

Introducing such learning-by-doing curves into existing large-scale energy system models was the topic of research of TEEM in the domain of applied mathematical modelling. Referring to Figure 1, the horizontal axis (installed capacities) is an endogenous variable of conventional energy models, whereas the vertical axis (unit capital cost) is an exogenous parameter. Through the curve of Figure 1, the unit capital cost becomes an endogenous variable and so an important complexity is introduced in the energy models. The research tested and evaluated mathematical programming methodologies for modelling this complexity. The research finally adopted two implementations of endogenous technological learning. The first implementation applies the learning by doing concept on the perfect

foresight cost-optimisation models ERIS, MARKAL, and MESSAGE. The second implementation, which in addition includes a learning-by-R&D mechanism, applies to market equilibrium energy models (i.e. PRIMES) and to system-dynamic/behavioural-oriented models such as POLES.

Lessons from the past

Among the various drivers, variations in energy prices clearly played a significant role in each wave of technical innovation in the energy sector over the past thirty years. Higher prices of energy motivate increasing the efficiency of converting energy sources and encouraging the penetration of more competitive sources of energy. This mechanism, however, is neither direct nor universal. For example, it was not an alteration in fuel prices that caused the decline in orders for nuclear reactors. Research into new fuels or car engine types is not a direct response to an increase in the costs of transportation, at least in the immediate term. Apart from fluctuations in price, which may provide suitable signals, it is often a systemic imbalance that triggers innovation. The more sudden and unexpected appearance of such an imbalance, the more powerful is the reaction.

Neither the incentive to innovation brought about by the structural limits of technical systems, nor the production of new knowledge that results, would have ensured the renewal of technology in the energy industries without radical reorganisation. The changes in organisation vary from one area of industry to another, but, in the recent past, also because of market globalisation, they have always had the effect of producing more specialisation and an increase in competition.

Both internal and external (to the individual firm) learning are important for technical change. Technical knowledge is seldom obtained 'off the shelf'. As processing and modifications are in most cases needed, contracting for R&D and licensing are usually complementary to in-house research. The tradeability and appropriability of technical knowledge are key factors for the role of public R&D.

In general, a number of stylised 'facts' emerge from the experience of the past fifty years. First, policy driven intensive R&D can accelerate technological improvement. Second, the accumulation of the installed capacity of a new technology induces a drop in capital costs. Third, the time required for the decline of capital costs of new technologies is highly uncertain. Fourth, the role of private R&D can also be highly effective in reducing the costs of a new technology but its concentration on long-term objectives may not be sufficient under certain market conditions.

The nature and role of learning

Although it seems quite plausible that additional funds can lead to additional learning, the only means by which this influence can be brought to bear, in most models, is through purchases that increase cumulative capacity. It would seem more satisfactory to have a functional relationship directly expressing the benefits expected from R&D funding. TEEM attempted to construct empirical formulations on this relationship but the dearth of data in this area proved to be a major obstacle on the way to robust results.

The empirical estimation of learning curves can use two different data samples: historical time series, as shown in figure 1, or cross-sectional data as shown in figure 2. The latter figure shows that even at the level of firms (data based on a survey of 108 cases of firms), there is high variability of learning rates. This is also confirmed when using time series. This variability is a major source of uncertainty when using learning curves in applied policy analysis.

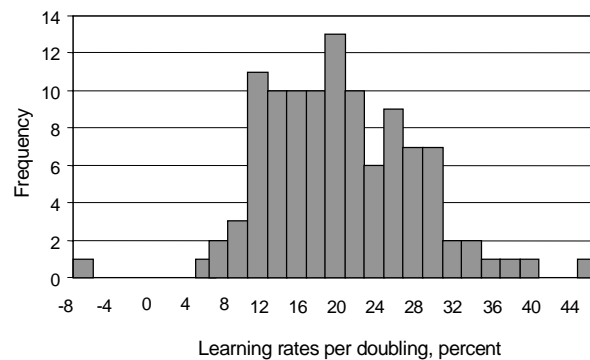


FIGURE 2. *Learning rates observed in 22 field studies.*

Source: Dutton and Thomas (Dutton and Thomas, 1984)

The empirical findings about the variability of learning rates suggest that the assumption about constant learning rates may be an oversimplification. The same analysis shows that learning rates are by no means erratic. This implies that if technological learning is monitored, the learning concept can serve as an indicator of success. In particular, this gives rise to the expectation that poor or even ‘negative’ learning, that is, decreasing performance with increasing installed capacity, if identified early, could help avoiding excessive sunk costs of research and development.

Care must be taken with the choice of the performance indicator that is used as a measurement of technological progress. In most cases, specific capital cost of a technology is a suitable parameter. There are cases, like for example the gas turbines, for which the thermal efficiency improvement is a more suitable indicator of technology progress.

The role of public R&D

Public energy R&D programmes may be a necessary but not a sufficient condition to achieve the technology improvements that are required to transform a prototype technology into a commercial technology. Many other factors or barriers often intervene, related to intrinsic characteristics of the technology and to its social acceptability or suitability for industry.

Some technologies, such as wind and biomass, despite limited cumulative R&D, have recently experienced important improvements and cost reductions; this also indicates that ‘scale of production’ economies and experience effects in the private domain also play a very important role in the continuous improvement of a technology and in the transition from prototype into commercial maturity. Experience effects obtained on early market developments – for instance in ‘niche-markets’ – may be essential for the development of commercially competitive new energy technologies.

One of the major challenges of R&D policy making is to strike a proper balance between providing support for currently emerging technologies, with good prospects in the short and medium term, and assisting in the development of currently less attractive options, that may become of crucial value to deal with longer-term challenges. It must be recalled that both exogenous and endogenous factors, which eventually determine the fate of any technology, are surrounded by uncertainty. R&D policies themselves can also play a hedging role by reducing the domain of uncertainties, as accumulating knowledge and experience.

5. Endogenisation of technical change

Scope of work

At the introductory stage of one of its core objectives, TEEM undertook an overview of the existing methodologies for modelling energy technology dynamics and examined the difficulties of endogenising technical change. The project then implemented two forms of endogenous technological learning.

The first implementation applies the learning by doing concept in the perfect foresight cost-optimisation models ERIS, MARKAL, and MESSAGE. These models build scenarios covering the post-Kyoto time horizon up to 2050 and include the effects from endogenous technology learning.

The second implementation also includes a learning-by-R&D mechanism as proposed for market equilibrium models, such as PRIMES, as well as for system-dynamic/behavioural models such as POLES. Both these policy relevant models implement endogenous technical change by assuming adaptive expectations. In the implementation by POLES there were a number of modelling innovations as, for example, the incorporation of cumulated R&D as an explanatory variable for technological progress and a portfolio analysis approach to the R&D

decision process. PRIMES incorporates induced technology change in the demand side where the acceleration in adopting advanced technologies by consumers, leads to improvements in terms of technology availability and costs, achieved through economies of scale in the supply of these technologies.

Conclusions on the methodology of modelling endogenous learning

The work carried out in the context of the TEEM project confirms that endogenous technological learning is a very promising new feature in energy system models. A key conclusion is that the incorporation of learning mechanisms in energy models is possible and feasible. Models extended in this way can deliver new insights and provide a framework to illustrate insights from innovation theory in a quantitative and consistent manner.

The two types of models used, i.e. perfect foresight models and adaptive expectation models are fundamentally different in character. This requires the learning feature to be introduced in different ways. Perfect foresight models endogenise technology characteristics according to their deployment by the model. Adaptive expectation models include the projected cost decline, associated with an expected growth in cumulative capacity, in the expectations and in the investment decisions of agents. POLES actually included R&D spending as an explicit driver of learning.

A mixed-integer programming (MIP) formulation has proven to be the best practical approach to model endogenous learning in perfect foresight, optimisation type of models. As the MIP formulation is only an approximation to the non-linear programming (NLP) problem, its accuracy depends on segmentation of step-wise linearisation of the cumulative cost curve. The first ERIS and MARKAL experiments have shown that the computational complexity can be handled adequately. These experiments also indicate that the solution time and the success in finding optimal solutions critically depend on specific solver options. These options are solver and problem specific and require some experimentation to find the most suitable practical settings. However, the permissible model size remains significantly smaller than the size of actual large-scale energy models. This is a limitation of modelling endogenous learning with perfect foresight.

The interaction between different technological clusters in terms of lock-in, lock-out, path-dependency, and spillover is clearly observed in some cases. The MARKAL model implementation has included the concept of key technologies and clusters. Compared to the first MARKAL experiments applied to the Western European energy system, this feature further enhances the consistency of the model outcomes, assuming the cost-breakdown and other additional parameters can be estimated and established well. The burden of using this new feature is more data collection work and increased but still reasonable solution times, compared to the first MARKAL experiments.

Besides the specific ‘learning’ uncertainties, which result from the absence of sufficient data on learning rates, other uncertainties (with perhaps more impact) are present in these types of energy models, even without the endogenous technology learning. Traditionally, such uncertainties are handled by considering different scenarios and sensitivity analysis. Perfect foresight energy system models like MARKAL and MESSAGE are capable of addressing certain classes of uncertainties more explicitly. For example, the stochastic version of MARKAL can come up with so-called ‘hedging’ strategies, i.e. development paths for the near term energy system with minimal regret for long-term time horizons.

Results from modelling endogenous technical change-learning

The TEEM project was, to a large extent, inspired and guided by the intensive debate around the Kyoto conference targets on greenhouse gas (GHG) emissions by developed countries. More specifically, the project was motivated by the role that present technology and spending on research and development (R&D) for the advancement of future technologies could play in the mitigation of climate change. In view of the long term nature of climate change and technological innovation, a key element of the design of the project was the incorporation of the substantial uncertainties surrounding both the future environment and the nature of possible technological advances and their likely costs and benefits.

The project focused on some of the main strategic issues that are currently at the core of EU policy, relating environmental externalities with the main energy and technology policy issues. These include future choices for centralised power generation, long-term prospects for renewables and fuel cycles, the energy efficiency gap and the impact of policy instruments (including fiscal instruments, subsidies, standards, R&D policy). The goal was to assist in the definition of some key elements of an integrated strategy that meets environmental requirements, whereas ideally is cost-effective, does not entail excessive differences in burden sharing and fosters the competitive position of the EU in the global market.

The research issue is shortly the following: if the climate change problem was likely to prove a major driving force of energy technology progress, how the climate change problem itself could be eased due to induced accelerated progress of energy technology.

Given the global dimension of the problem and the globalisation of the market for energy technologies, TEEM had to take into account the size of the world market for the various technologies and the implications for EU industry and its competitiveness. It had also to consider the context of energy market liberalisation in the EU, the global competition that may be encouraged by the Kyoto flexibility mechanisms (emission trading, joint implementation and clean development mechanisms) and the impact of world energy resources and prices on technology progress and policy. This also explains why TEEM used a series of energy models, covering both the World and the European scales.

A key objective of the project was the evaluation of the impacts of technology development on the energy system and the environment as well as on the distribution effects on countries in Europe and other regions. Thus, in some respects, this work updated and improved previous analysis on these issues carried out under the “Climate Technology Strategy within Competitive Energy Markets” project, which has preceded TEEM under the 4th European Commission Research Framework programme (Capros *et al*, 1999a and Capros *et al*, 1999b).

The research started by preparing a set of EU and global projections of all relevant driving factors for the period to 2030. These factors include the quantities of energy demanded and supplied by sector and fuel, the technologies used in each sector and the degree of expected technology progress under baseline conditions. As a result of this baseline projection work, TEEM published a detailed world and European energy system scenario for the period to 2030. A series of alternative scenarios, quantified by using the models, served to explore the relationships between technology progress and climate change compliance of the future energy system. The analysis explored how climate change may drive technology progress and how technology progress may improve the cost-effectiveness of climate change mitigation policies.

Given the data and methodological problems involved, most of the results obtained from the endogenisation of technical change and/or of learning must be seen as illustrative. The models used for the purposes of the project are at different stages of experimentation with the endogenisation of technical change, adopt extremely different approaches and include models that are meant to be analytically pure and innovative as well as models whose primary objective is policy relevance. Despite these differences, a number of general conclusions can be drawn.

Incorporating the learning by doing concept makes an important difference. A comparison between the original models with exogenous cost projections (either as constant costs over time or assuming a regular decline over time) shows that the resulting technology prospects differ substantially.

There are benefits of investing early in emerging technologies that are not competitive at the moment of their deployment.

Several types of RTD interventions can accelerate the market penetration of new technologies. The directions into which such interventions might lead have been illustrated in some of the experiments.

The results of the post-Kyoto analyses indicate that estimates of the cost of CO₂ reduction will be lower if the concept of endogenous technology learning is adopted. Policy measures aiming at CO₂ emission reduction are shown to have a clear and often decisive positive

impact on the prospect of clean technologies, underlining their important role in guiding technology development towards more sustainable directions.

6. Data issues and future research

Despite the significant progress made within the TEEM research project, it seems that there is still considerable uncertainty to draw robust policy conclusions. The uncertainty regards both the magnitude of the learning mechanisms as induced by external factors and conversely the externalities generated by technological spillover and the recommendation about appropriate levels, orientations, and processes for optimising public R&D portfolios. Especially for the latter domain, the uncertainties are such that only simplified mechanisms and stylised questions can be envisaged for exploration and analysis in modelling experiments. Therefore further research is necessary in both areas.

The scale, at which learning takes place (global, regional), will certainly affect the development of technology. The spatial dimension of technological learning and the possibilities of learning ‘spillover’ are aspects that deserve further investigation. Uncertainty is, together with learning, at the core of the endogenous mechanisms of technological change, so future work should also be devoted to a more thorough exploration of the effects of uncertainty both on learning rates and other policy conclusions.

An important conclusion is that the estimation of the data required for endogenising learning is not straightforward. This is due to the lack of adequate statistics, the requirement of high quality regarding the accuracy of some data (e.g. the cumulative capacity and initial costs in the starting period) and the large sensitivity of the results with respect to these parameters (e.g. value of progress ratio). For some models these concerns have led to dampen out seemingly unrealistic results by additional mechanisms and characteristics, such as floor costs and gradually declining learning elasticities. These additional aspects again require many new assumptions and data, each again with their own uncertainties. There is a need for investigating further and in more detail the value of the required data, such as the progress ratio, maximum cumulative capacity in the end year, initial installed capacity and initial costs.

A new European research project, namely SAPIENT, started in 2000 under the 5th Framework Research Programme of the European Commission. The aim is to continue the research of TEEM and to re-visit the energy-environment-technology systems analysis (for Europe and the World), so as to attempt to measure the value of achieving accelerated technological progress in energy demand and supply and evaluate the policy instruments that could generate such progress. A key feature of the SAPIENT approach is the elaboration of a small meta-model, which will explore the links between policies related to RTD (public and private) and the benefits from technological progress. These benefits will be modelled through reduced-form relationships reproducing approximately the relevant behaviour of

existing large-scale models for the European and World system and obtained by consecutive runs of these models. The large-scale models will also be used to evaluate the consequences of policy on energy demand and supply, the state of the environment and the economy. The role of the meta-model will be to explore a domain of optimal R&D strategies in a context of uncertainty (i.e. incorporating notions of hedging) and in the presence of multiple objectives as is appropriate when considering public sector participation in R&D initiatives.

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