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# Energy Technology Dynamics and Advanced Energy System Modelling

**Contract JOS3-CT97 0013**

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**Project Partners:** ***ICCS/NTUA (co-ordinator), ECN, ESD Ltd., IEPE/CNRS, IER, IIASA/ECS, IPTS/JRC, CES/KUL, PSI, ECOSIM Cons. Ltd, Mr. E.L. Vouyoukas, MERIT, CRES.***

# FINAL PUBLISHABLE REPORT

**Written by all Partners and edited by P. Capros and E.L. Vouyoukas**

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# 1. Project Objectives and Methodology

## 1.1 Objectives

The general objective of the “Energy Technology Dynamics and Advanced Energy System Modelling” project TEEM project was to research and develop model based analysis on energy technology dynamics and their changes as induced by policy. In modelling terms the research was aimed at representing energy technology progress as an endogenous process within the energy system models.

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. There are 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.

The 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 focussed on some of the main strategic issues that are currently at the core of EU policy, relating environmental externalities with the main energy technology and 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, RTD policy). The goal was to assist in the definition of some key elements of an integrated strategy that meets environmental requirements, is cost-effective, does not entail excessive differences in burden sharing and fosters the competitive position of the EU in the global market.

The climate change problem is likely to prove a major force of energy technology progress. This work however, also takes into account the world market for the various technologies and the implications for the EU industry and competitiveness. The context of energy market liberalisation in the EU, as well as the global competition that may be encouraged by the Kyoto flexibility mechanisms (emission trading, joint implementation and clean development mechanisms) is also considered, as is the impact of world energy resources and prices on technology progress and policy.

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 the EU and the World. Thus, in some respects, this work updates and improves previous analysis on these issues carried out under the Climate Technology Strategy within Competitive Energy Markets project, which was also carried out under the Joule III programme (Contract JOS3-CT95-0008).

One of the major objectives of TEEM was to assist in the appraisal of costs and benefits of technology development and the estimation of the expected value of RTD in the energy field. This 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 RTD expenditures – and thereby about the economic value of TEEM results – seem possible at this stage.

In order to carry out the above tasks, a set of EU and global projections of all relevant driving factors for the period to 2030 was necessary. These variables include the quantities of energy demand and supply by sector and fuel, the technologies used in each sector and the degree of technical change. Thus, an additional objective of the project was to update previous analysis and model results in order to obtain a set of projections that include the most recent data and up to date information on likely technological developments over the next thirty years.

The project also had analytical and methodological objectives, including the accommodation of novel concepts in the analysis. The treatment of technological progress in applied macroeconomic and energy models was traditionally based on the inclusion of an exogenous variable that reflects the assumed rate of technological advance. While this approach is also used in this work, the TEEM project aimed at examining 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. A number of qualitative and quantitative results are presented in later sections that are based on endogenous growth. 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 EU.

Thus, this work also reports on the efforts, within the TEEM project, to specify and develop 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 dynamic effects of RTD 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., is also examined.

## 1.2 Methodology

The main environmental subject of the TEEM project was the threat of adverse climate change. A major characteristic of this problem is the high uncertainty surrounding the potential damages of future climate change, which could be very significant. Methodologically, this situation of high uncertainty combined with high potential impacts is strikingly similar to the economics of RTD, which is also characterised by potentially significant consequences (in this case, benefits) and high uncertainties at the same time. The subject of TEEM ties these two together. However, in both cases a full quantification remains a challenging and unfinished task. Thus, the expected impact of TEEM results that are presented here is of exactly the same nature as its two constituent problem areas, climate change and RTD 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. Until today, there has been no systematic energy modelling methodology that incorporates endogenous technology dynamics and their interaction with policy making. 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 project as listed below. In most modelling efforts until today, technical progress has been assumed as autonomous, without being affected by policy instruments or private incentives. However, it can be argued that technical progress is very much affected by policies and market conditions: a clear result of this is the wind energy cost reduction, by more than two thirds in the 80s, as a result of the market that was created in California. Thus, the project focussed 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 reported are based on purpose built models that seek to analyse at least at a highly aggregated level, some of the issues involved in the endogenisation of technology and the nature of technological expectations.

Despite the progress reported in this study a number of methodological, data and other difficulties remain in the analysis of the issues covered in this study. 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.

## 1.3 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), SAFIRE (ESD) 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 technico-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.

### *ERIS*

ERIS (Energy Research and Investment Strategy) is a global energy model prototype specified and developed in the context of the TEEM project. 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 programing (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.

### *MES SAGE*

MESSAGE is a dynamic linear programming model that is specifically suited for complex, multi-regional models. 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 endogenises 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*

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 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 outlined above are additive in nature, that is they can be used in combination with each other, and are embedded in one 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.

### *PRIMES*

From the very beginning, in 1993-1994, the PRIMES energy model was designed to focus 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 including the relationships between energy policy and technology assessment. The need to represent the growing process of market liberalisation, also motivated other modellers to adopt market-oriented modelling approaches giving rise to models often called “new generation models” PRIMES follows a similar 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-set for all European Union member states.

*POLES*

The POLES model is a global 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, 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. The development of the POLES model has been partially funded under the JOULE II and JOULE III programmes of DG XII of the European Commission. Since 1997 the model is fully operational and can produce detailed long term (2030) world energy and $CO_2$ emission outlooks with demand, supply and price projections by main region.

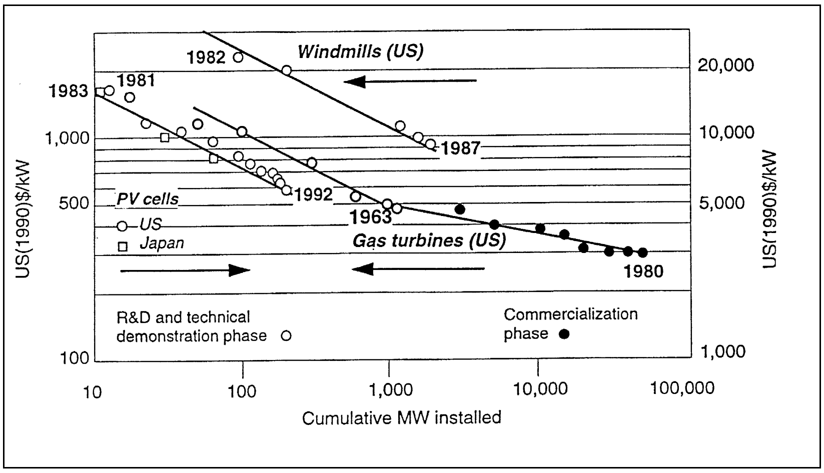
# 2. The history and theory of technology dynamics

## 2.1 Scope of work

The project dealt with a number of concepts on technology dynamics that have been developed in the very rich literature on technical change. An historical analysis of the three main waves of technological changes that profoundly altered the energy sector over the past thirty years and the key factors that were responsible for these changes were examined. Empirical analysis was carried out on two of the most important such factors, namely, public research and development spending and learning rates. Both these factors and assumptions on their future development play a key role in the model results. An analysis of the kinds of uncertainty involved in the analysis of technological progress and their importance for policy was also carried out.

The main conceptual and empirical construct used in the project is the learning by doing curve. It shows a reduction of capital costs (purchasing costs) 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 RTD 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 the main new energy technologies. Data were collected for this purpose. The learning rates resulting from the econometric estimations have been used in all model applications.

Figure 1: Historical Examples of Learning Curves relating Capital Costs to Cumulative Installed Capacity



## 2.2 Lessons from the past

The variations in energy prices clearly played a significant role in each wave of technical innovations in the energy sector over the past thirty years. Price increases tend to increase the efficiency of converting energy sources and to encourage renewable 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 engine types is not a response to an increase in the costs of transportation, at least in the immediate term. Apart from fluctuations in price, which may provide signals, it is often a systemic imbalance that triggers innovation. The more sudden and unexpected its appearance, the more powerful 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 no doubt vary from one area of industry to another, but, in the recent past, 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.

## 2.3 The nature and role of learning

Although it seems immensely 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 expressing the benefit of research and development more directly. Work within the TEEM project has therefore begun to add the effects of R&D to the formal description of technological progress. That work is still very much in its initial phases, however, and theoretical difficulties as well as the dearth of data in this area is a major obstacle on the way to robust results. With or without an accurate estimate of the costs of inducing technological learning, the learning rates observed in the past hold great promises for the benefits of technological progress.

Figure 2: Learning rates observed in 22 field studies

Source: Dutton and Thomas, 1984.

The analysis of the variability of learning rates suggests that the assumption of constant learning rates may be an oversimplification. The same analysis shows, however, that learning rates are by no means erratic. This means that if technological learning is monitored, the learning concept as used here 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, can be identified early, thus avoiding excessive sunk costs of research and development.

Care must be taken with the choice of the performance indicator that is to measure technological progress. In most cases, specific capital costs of a technology are a suitable parameter. For gas turbines, for example, efficiency improvements are included in this indicator, because their capital costs are usually given in terms of electricity output.

### 2.4 The role of public R&D

Public energy R&D programmes maybe a necessary but not a sufficient condition to provide in all cases the technology improvements which are required to transform a pilot technology into a market technology. Many other factors or barriers should be considered, from the intrinsic characteristics of the technology to its social acceptability or suitability to the industry context.

Some technologies with limited cumulative R&D, such as wind and biomass, have recently experienced important improvements and cost reductions; this also indicates that "scale of production" economies and experience effects due to learning by doing phenomenon have a very important role in the continuous improvement of a technology and in the transition from pilot to market technology. Experience effects obtained on early market developments − for instance in "niche-markets" − may be essential for the development of fully competitive new energy technologies.

One of the major challenges facing RTD policy making is to strike a proper balance between providing support for currently emerging technologies, with good prospects on the short and medium term, and development of currently less attractive options, that may become of crucial value to deal with longer-term challenges. In doing so, it must be recalled that both exogenous and endogenous factors that eventually determine the fate of any technology are surrounded by uncertainty. R&D policies themselves can play their part in reducing the endogenous uncertainties, as accumulation of knowledge and experience reduces these uncertainties. Due attention is still needed, however, to accommodate the impact of the exogenous uncertainties in the RTD policy making process.

## 3. Energy outlook and the role of technology

### 3.1 Scope of work

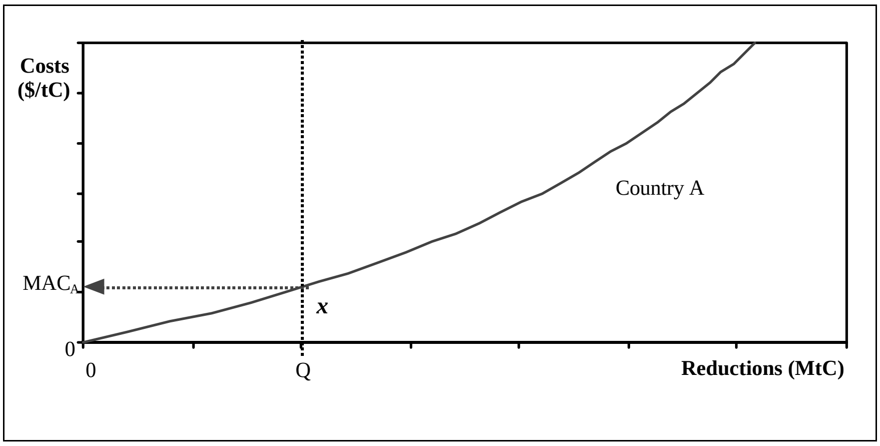
In order to assess the consequences of world $CO_2$ emission constraints as well as the value of technological progress in meeting these targets, the development of a set of reference projections of the global and European energy outlook to 2030 was essential. This is also important for evaluating the technologies that are likely to be required for meeting any emissions targets. It will be seen that despite the assumed significant advances in a number of technologies, under Reference scenario assumptions, global emissions continue to grow significantly over the outlook period. The outlook also provides critical information on the potential size of the market for each technology. This data is then used in the determination of the future cost of each technology.

The project also identified the key uncertainties surrounding the future dynamics of the energy system, namely those concerning world economic growth and world oil and gas resource endowments, and examines the implications of these uncertainties for the outlook of international energy prices. The key energy features of the baseline outlook of the European energy system and of the role of technology progress in the demand and the supply side were also examined. Emphasis was given on the role of technological improvement both in the short and the long run.

The objectives of TEEM also included the examination of the potential role of flexibility mechanisms, including emission trading, in reaching the Kyoto targets as well as the costs and benefits of technological progress in the longer term. In order for these objectives to be carried out marginal cost abatement curves (MACs) were estimated both for the EU and many world regions. As shown in Figure 3, the total abatement cost corresponds to the area below the MAC curve between zero and the target; for country A, it equals the area *0Qx*. The total abatement cost therefore depends both on the planned reduction and on the shape of the MAC curve.

In order to examine the role of technology in reducing emission in the post 2010 period, a new post Kyoto scenario was introduced, with emissions significantly below those of the reference scenario, as well as a number of "technology stories", or scenarios in which a specific cluster of technologies is assumed to progress more rapidly than assumed in the reference and post Kyoto scenarios. Finally, the project used the scenarios developed by IIASA, in the context of WEC for some analysis of the period beyond 2030.

Figure 3: Marginal abatement cost curves



## 3.2 Key assumptions of the reference outlook

According to the reference scenario developed within the TEEM project, world population and economic growth will remain the key drivers for energy development in the next decades. The link between population, GDP and energy has considerably weakened in the last quarter of a century in industrialised countries. With an average 2 % pa growth in the 2000-2030 period, and less than 2 % pa in the last decade of the projection, OECD regions experience the lowest growth rates. In the economies in transition, the assumed recovery from very low levels of activity in the late 1990s results in sustained growth rates, of more than 4 % pa in Eastern Europe and of 5 % pa in the Former Soviet Union. In the developing regions, the growth rates are projected to be both higher and less differentiated among regions than in the last decade. All of these regions experience growth rates ranging from 4 % pa. There will be a strong decrease in the yearly growth rate of world population from the current level of 1.6 % pa to an average 1.2 % pa between 2000 and 2030.

In the period 2000-10, the annual economic expansion is projected to be around 2.4% while, in the period after 2010, it is limited to less than 1.8%. The EU population is projected to increase by only 12 million people in the period to 2010 and to be effectively stable after that.

The reference case projects an increase in the world oil price to 30 $90/bl in 2030.

## 3.3 Global Outlook to 2030

According to the reference scenario, world energy consumption may almost double, between now and the year 2030; this is due to the sustained economic growth, allowing for some convergence of the GDP per capita of the emerging regions of the world to that of more advanced regions.

The impact of economic growth is significantly moderated by the impact of an average energy efficiency improvement of 1.1 % per annum (pa), due to the combined effects of structural changes in the economy, of autonomous technological progress and of energy price increases.

World $CO_2$ emissions grow at a slightly higher rate than energy consumption, due to a very slow development of nuclear energy, while the supply from renewable sources increases very rapidly but remains limited in absolute terms.

In 2030, fossil fuel supplies represent almost 90 % of total world primary energy. Oil remains the main source (34 %) of energy with a significant part of oil supply coming from non conventional resources (14 % total oil). Coal is the second biggest source of supply (31 %) and two thirds of the increase in coal consumption between now and 2030 comes from the Developing Asia region. Natural gas, despite its very rapid growth in the power generation sector, represents only one fourth of world energy supply by 2030, partly because its development is somewhat limited by price increases along the period considered.

Table 1: POLES reference outlook, World

| POLES - REFERENCE WORLD | | 1990 | 2000 | 2010 | 2020 | 2030 | y.a.g.r. 2000-30 |
|---|---|---|---|---|---|---|---|
| Population | Million | 5 249 | 6 150 | 7 027 | 7 893 | 8 713 | 1.2 |
| Per capita GDP | 90$/cap | 5 217 | 5 714 | 7 142 | 8 862 | 10 732 | + 2.1 |
| GDP | G$90PPP | 27 383 | 35 138 | 50 187 | 69 945 | 93 514 | = 3.3 |
| Energy intensity of GDP | toe/M$90 | 313 | 266 | 229 | 209 | 192 | + -1.1 |
| Primary energy | Mtoe | 8 338 | 9 359 | 11 517 | 14 639 | 17 944 | = 2.2 |
| Carb intensity of energy | tC/toe | 0.70 | 0.69 | 0.71 | 0.73 | 0.75 | + 0.3 |
| CO2 Emissions | MtC | 5 863 | 6 443 | 8 188 | 10 692 | 13 411 | = 2.5 |
| Primary Energy Supply | Mtoe | | | | | | |
| Solids | | 2 205 | 2 206 | 2 997 | 4 160 | 5 528 | 3.1 |
| Oil | | 3 246 | 3 664 | 4 303 | 5 133 | 6 033 | 1.7 |
| Gas | | 1 703 | 2 085 | 2 710 | 3 657 | 4 484 | 2.6 |
| Others | | 1 183 | 1 404 | 1 507 | 1 689 | 1 900 | 1.0 |
| *of which* | | | | | | | |
| Nuclear | | 433 | 602 | 623 | 687 | 759 | 0.8 |
| Hydro+Geoth | | 184 | 224 | 279 | 341 | 408 | 2.0 |
| Trad.Biomass | | 412 | 401 | 340 | 291 | 251 | -1.6 |
| Other Renewables | | 155 | 177 | 265 | 370 | 481 | 3.4 |
| World Oil Price | $90/bl | 23.8 | 11.1 | 19.1 | 25.0 | 30.3 | 3.4 |

Apart from the uncertainties on the status of technology, two sets of key uncertainties have been considered in order to develop alternative cases to the Reference scenario:

- The first one relates to economic growth. The low-growth or “Protracted Crisis” scenario ends up with levels of total GDP, primary energy consumption and $CO_2$ emissions which are respectively 8 %, 6 % and 7 % lower than that of the Reference. In this scenario the resource and emission constraints may be eased, but to the very high cost of a much reduced per capita GDP, particularly in the developing regions of the world, which would then experience a new “lost decade” in the 2000-2010 period;
- The second one relates to oil and gas resources endowments. The “Abundance” case provides a largely different picture of the world energy future because of an increased availability in hydrocarbons. This leads oil and gas prices in 2030 to be much lower than in the Reference, inducing higher world energy demand and a significant increase in the demand for oil and gas. Gas consumption by 2030 is 23% higher than in the Reference case, partly at the expense of coal whose demand declines. $CO_2$ emissions are 2.6% higher than in the Reference case.

## 3.4 EU Outlook to 2030

Even though the GDP of the EU is expected to more than double between 1995 and 2030 in the reference scenario, primary energy needs exhibit a significantly lower increase of about 20%. This is the result of an average energy intensity improvement of 1.7 pa in 1995-2030, which is due to structural changes in the economy, saturation of energy needs and autonomous technical progress.

The role of fossil fuels increases over time and they account for about 85% of primary energy needs in 2030, compared to 80% in 1995. The large scale decommissioning of nuclear plants combined with the rather moderate penetration of renewable energy forms in the EU energy system lead to this result. Oil remains the main energy source, followed by natural gas and solids. The latter exhibits a significant comeback in 2020-30 as coal plants are used to replace decommissioned nuclear capacity. The share of coal drops from 17.5% in 1995 to 12.5% in 2010 and then increases to 14.2% in 2020 and 19.3% in 2030. The share of natural gas increases from 20% in 1995 to almost 27% in 2030, driven almost exclusively by the growth in the use of gas turbines in power generation.

Under baseline assumptions the EU will not meet its Kyoto undertakings, at least through energy related $CO_2$ emissions. Despite the assumed significant increase in oil prices, instead of the 8% reduction in emissions by 2010 a 5.8% increase is projected. The increase in emissions reaches more than 17% in 2030, when compared to the level of $CO_2$ emissions in 1990. Depending on the outlook and policy measures for non $CO_2$ greenhouse gases, such as CH4, it is clear that a number of policy initiatives will have to be undertaken for the abatement of energy related emissions.

The outlook for nuclear power is one of the key uncertainties regarding the EU energy system in the longer term. Nuclear can play a very significant role in reducing emissions beyond 2010. Its impact will depend on whether the massive amount of nuclear plants that are due to be decommissioned between 2015 and 2030 will be replaced by nuclear plants or by fossil fuel plants.

Table 2: PRIMES reference outlook, EU15

| | Mtoe | | | | | %Annual growth rates | | | | Shares, % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1995** | **2000** | **2010** | **2020** | **2030** | **95/10** | **10/20** | **20/30** | **95/30** | **1995** | **2010** | **2020** | **2030** |
| **Total** | **1363** | **1447** | **1524** | **1565** | **1550** | **0.7** | **0.3** | **-0.1** | **0.4** | | | | |
| Solid Fuels | 237 | 204 | 191 | 222 | 300 | -1.4 | 1.5 | 3.1 | 0.7 | 17.4 | 12.5 | 14.2 | 19.3 |
| Liquid Fuels | 574 | 608 | 633 | 631 | 602 | 0.7 | 0.0 | -0.5 | 0.1 | 42.1 | 41.5 | 40.3 | 38.9 |
| Natural Gas | 273 | 332 | 394 | 402 | 412 | 2.5 | 0.2 | 0.3 | 1.2 | 20.1 | 25.9 | 25.7 | 26.6 |
| Nuclear | 205 | 223 | 216 | 196 | 117 | 0.3 | -1.0 | -5.0 | -1.6 | 15.1 | 14.2 | 12.5 | 7.6 |
| Electricity | 1 | 2 | 2 | 2 | 2 | 4.2 | 1.7 | 0.6 | 2.5 | 0.1 | 0.1 | 0.1 | 0.2 |
| Renewable En. Sources | 72 | 78 | 88 | 112 | 116 | 1.4 | 2.4 | 0.4 | 1.4 | 5.3 | 5.8 | 7.1 | 7.5 |
| Energy intensity (toe/MEUR90) | 240 | 224 | 186 | 159 | 134 | -1.7 | -1.5 | -1.7 | -1.7 | | | | |
| Energy per capita (toe/cap) | 4 | 4 | 4 | 4 | 4 | 0.5 | 0.2 | -0.1 | 0.3 | | | | |
| Import dependency (%) | 47.5 | 49.2 | 56.4 | 63.8 | 72.2 | 1.1 | 1.2 | 1.2 | 1.2 | | | | |

Another uncertainty of the baseline outlook is that of the evolution of international fuel prices. Under the assumption of higher availability of resources and therefore lower prices for crude oil and natural gas, the observed expansion in the use of solids in the power and steam generation would not occur and $CO_2$ emissions in the long run would be substantially lower.

It is important to note that the role of technology in dampening energy demand and emissions is extremely important even under baseline conditions. Technological improvement, leading to energy efficiency gains, is the key factor behind the 1.7% pa reduction in energy intensity in the 1995-2030 period.

## 3.5 The role of flexibility mechanisms for meeting the Kyoto targets

One of the objectives of TEEM was to examine the potential role of technology in meeting the targets set at the Kyoto conference and to compare the value of technology change with the cost of meeting the Kyoto targets. The likelihood of the Parties to Annex B introducing flexibility mechanisms depends on their willingness to make reductions in greenhouse gas emissions while respecting the principle of economic efficiency. The project examined the role of flexibility mechanisms at two levels. First, the POLES model was used to examine the economic impact of these flexibility mechanisms. The possible impacts of emission trading in Annex B were identified as well as, in a more hypothetical case, at least for the 2010 horizon, of a world market for emission permits. Second, the PRIMES model was used to assess the costs and impacts for the European Union energy system of meeting the Kyoto target under different flexibility schemes. The value of technology change or the additional cost required for the achievement of the Kyoto target in the absence of technical progress in the EU energy system was also evaluated.

The extent of international flexibility is one of the most crucial issues as regards the size of marginal abatement cost (MAC) required to achieve the Kyoto target at a world level. It has been shown the MAC varies between 20 \$/tC and 200 \$/tC in some regions, depending on the flexibility schemes.

The total cost of meeting the Kyoto targets is also highly sensitive to assumptions on flexibility mechanisms. For example, this cost is reduced from \$47 billion in the case of no flexibility to \$12 billion under the assumption of full emission trading among Annex B countries.

The main argument against the introduction of flexibility mechanisms is that, through the lower cost of emission abatement, they will lead to more limited development of new technologies as their advantage in terms of emissions becomes less valuable. However, while this argument cannot be ignored one must not disregard the fact that the higher the flexibility the lower the costs of achieving the Kyoto target, making political acceptance and compliance to the Kyoto protocol much easier. In addition, in the full trading scenario developing countries can be financed from Annex B countries, through trading of pollution permits. Last but not least, even though a large flexibility on emissions trade may reduce competitiveness of new technologies in the short term, it may also considerably enlarge the market for these technologies in the long run.

The findings from the analysis of the EU energy system confirm the significance of international flexibility in the achievement of the Kyoto target. The cost of achieving the Kyoto target drops by almost 75% in the case of full trading compared to the no trading case for the European Union. This occurs to the detriment of technology improvement. However, the analysis showed that the technical progress that occurs even in the absence of any emission reduction target in the period to 2010 for the EU energy system, is of great importance for the limitation of EU emissions and its realisation should be ensured. The cost benefit resulting from this technical progress is 1.5 times higher than the cost required to achieve the Kyoto target in the absence of trading mechanisms.

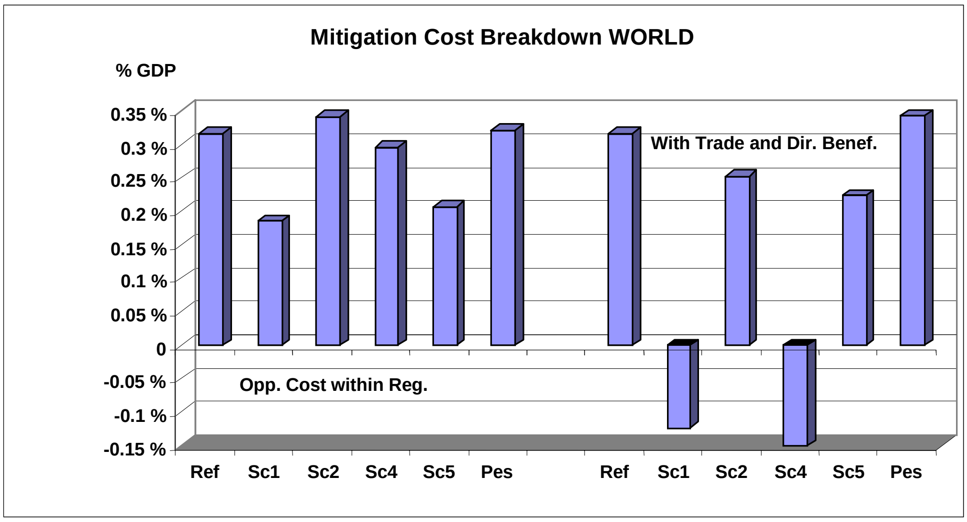
## 3.6 The Role of Technology in Reducing Emissions beyond 2010

The “technology story” scenario assumptions represent particularly optimistic trajectories for future Technico-economic performance of clusters of generically linked technologies. Their simulation using the POLES and PRIMES models shows that they could have a major impact on world and EU energy demand and supply configurations.

In the absence of carbon constraints, the technology scenarios make only a small contribution to solving the world’s $CO_2$ emission problem. This is due mainly to their sectoral nature (affecting only a segment of the energy system), to the fact that many of the scenarios involve fossil fuel technologies (making them attractive vis-à-vis less polluting or non-fossil ones) and also because they set into motion secondary effects (such as lower prices for the more polluting fuels) which tend to neutralise, at least partially, some of the benefits in terms of $CO_2$ emissions.

The analysis points to the conclusion that the magnitude of the world-wide $CO_2$ problem is such that it is hard to see how clusters of technologies unassisted by more general policy measures could make a major impact. It is precisely such general policy measures that were introduced in the form of $CO_2$ emission targets affecting all countries of the world and envisaged as an extension of the Kyoto agreement to the year 2030. These targets were set at levels that are compatible with the stabilisation of world emission levels after 2020. Furthermore, free trade in emission permits was assumed.

Figure 4: Mitigation cost with and without emissions trade



The results obtained by combining some of the technology scenarios with such a strict general emission reduction context have been very encouraging in terms of the efficacy of technological breakthroughs. Equilibrium permit prices were sometimes lower than in the absence of the assumed additional technological progress while the direct system cost of meeting the targets was reduced very substantially becoming negative in some cases if direct benefits were taken into account.

The technology stories produced substantial cost benefits throughout the major regions of the world while at the same time producing a better distribution of the burden between the electric and non-electric sectors. Part of these benefits was due to the incorporation of emissions permit trade, which ensured the efficiency of effort without as it happens affecting equity negatively.

Table 3: Value of technology change in achieving the post-Kyoto target under alternative technology stories, 2030

| | Post Kyoto | Nuclear story | Hard coal story | Gas and fuel cells story | Renewables story | Demand side story | All technology stories |
|---|---|---|---|---|---|---|---|
| Required carbon value (EUR'90 per tn of carbon avoided) | 178 | 116 | 210 | 93 | 153 | 79 | 40 |
| Cost of abating CO2 emissions within the EU energy system (MEUR'90) | 17228 | 7153 | 20642 | 7261 | 12140 | 4264 | 1740 |
| as % of GDP | 0.15% | 0.06% | 0.18% | 0.06% | 0.10% | 0.04% | 0.02% |
| Value of technology change (MEUR'90) | 0 | 10075 | -3413 | 9967 | 5088 | 12965 | 15488 |
| as % of GDP | | 0.09% | -0.03% | 0.09% | 0.04% | 0.11% | 0.13% |

Results for the EU are broadly compatible with the above. In general, technological progress tends to reduce significantly the cost of reaching a pre-specified emissions target in the post 2010 period. An exception to this occurs when a breakthrough takes place in a carbon intensive technology, such as coal. In this case, the energy system would have a tendency to become more carbon intensive than in the absence of the breakthrough. Consequently, any emissions target would require a larger reduction than would be the case in the absence of the breakthrough.

It is important to note that all supply side technological improvements result one way or another in a reduction in the cost of consuming energy and hence potentially cause consumption to increase. In any case, it is hardly surprising that the scenarios involving non-fossil energy (the nuclear and renewable scenarios) have produced markedly better outcomes as far as $CO_2$ emissions are concerned.

A demand side technology scenario, run for the EU with PRIMES, indicates that demand side technological improvements could play a key role in reducing the cost of reaching emissions reduction targets.

In summary, the main result of the analysis seems to be that technological breakthroughs cannot in themselves resolve the problem of $CO_2$ emissions and concentrations. However, if something drastic has to be done about emissions, these same breakthroughs can render the task considerably lighter.

## 3.7 The Period beyond 2030

Due to the long-term dynamics determining the global climate, the full effect of a given mitigation strategy is brought to bear only over many decades. It is therefore useful to put the medium-term scenarios developed for the purposes of TEEM into the context of longer-term studies. Such a context can give an indication of possible plausible continuations of the medium-term scenarios and thereby an idea of their longer-term impacts. The IIASA-WEC scenarios chosen for this “embedding” are defined for the time period from 1990 to 2100 and some illustrative examples of generic technologies that could contribute to a low-carbon energy future are discussed separately. In this context, the project also examined some strategic aspects of European energy RTD policies.

Scenarios for the period beyond 2030 are generally optimistic regarding technology change. This optimism is necessary if significant climate change is to be avoided. However, only major and sustained efforts in the R&D area will justify the rates of technological progress assumed in the scenarios. At the same time, historical rates of progress justify the hope that the R&D efforts will be successful also in the future. Technological progress will have to materialise in particular in the non-fossil fuels sector. This conclusion holds for the primary energy sector, where nuclear energy and renewables dominate, but also for the end use sector. There, in addition to a continuing “electrification” of the energy system, energy services that are provided today by liquid oil products will need to be increasingly met by end-use technologies that use carbon-free fuel inputs. A prime candidate for such a solution is the fuel-cell technology. The hydrogen needed for its operation could eventually be provided without generating carbon emissions along the way. In a transition phase leading to this goal, natural gas can play an important bridging role.

In the midst of discussing technological development, it also seems important to remember the importance of life style, which can alter dramatically in the long run. Life style is the major determinant of the energy intensity of energy services such as transportation. The final-energy intensity of passenger transportation, for example, is most easily cut by a factor of (almost) four if four persons instead of one ride an automobile. Energy savings potentials of this magnitude cannot be neglected in any assessment of carbon mitigation strategies, and the study of life style and its possible change should therefore be included in the consideration of long-term energy strategies.

# 4. Endogenisation of technical change

## 4.1 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 develop new scenario results covering the post-Kyoto time horizon up to 2050 and including endogenous technology learning. These results comprise those from the simplified global ERIS prototype and from the large scale MARKAL model for Western Europe. The multi-regional version of the ERIS model prototype examines electricity generation technologies in a global context with endogenous technological learning curves. Impacts of Kyoto-like $CO_2$ constraints are analysed considering the effects of allowing or not trade of emission permits. Complementary stochastic analyses addressing the uncertainty of emission constraints, demand and learning rates and a preliminary assessment of the effects of the geographical scale of learning are also presented. In addition, several sensitivity analysis runs of ERIS explored the impact from varying learning rates and the role of different sets of world fuel prices.

Much experience was also gained from experiments with the comprehensive energy system model MARKAL for Western Europe, including endogenous technology learning based on the learning-by-doing mechanism. These experiments have confirmed the benefits expected from adoption of the mechanism. The work with MARKAL takes into account the interdependency between (families of) technologies, rather than considering individually learning technologies. The results indicate that the new ‘cluster feature’ improves the internal consistency and allows for assessment of spill-over and cross-over effects, and other mechanisms identified in technology dynamics.

The second implementation also includes a learning-by-R&D mechanism as proposed for optimisation/equilibrium-oriented models, such as PRIMES, as well as for system-dynamic/behavioural-oriented 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 innovations. These include the incorporation of cumulated R&D as an explanatory variable for technological progress and a portfolio analysis approach to the R&D decision process. With the new module, POLES captures both the supply and demand sides of the energy technology market. Due to the model specification chosen, energy capital equipment price is therefore influenced by two factors, one controlled by demand (cumulative capacity) and the other by supply (cumulative R&D effort). Despite data weaknesses, the POLES experiments with endogenous learning result in a number of interesting implications for public R&D policy.

PRIMES incorporates induced technology change in the demand side. The introduction of emission reduction constraints affects the dynamics of technology change compared to baseline conditions through interrelated effects coming from the technology supply and the consumer side. The acceleration in adopting advanced technologies by consumers, in their effort to reduce emissions, leads to improvements in terms of technology availability and costs, achieved through economies of scale in the supply of these technologies. The reported results include those from a ‘no-learning’ case, where consumers are assumed to lack perception of emission reduction targets as regards their decision on new equipment, and a “fast learning” case. In the latter, the consumers are considered to fully understand the opportunities offered by advanced technologies and are willing to take the corresponding opportunity cost without taking into consideration issues related to technology maturity and reliability.

## 4.2 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 treated, perfect foresight models on the one hand and adaptive expectation models on the other hand, are fundamentally different in character, which implies that also the learning feature is introduced in different ways. In perfect foresight models this is done by endogenising the change of the technology characteristics of the technologies according to their deployment by the model. In adaptive expectation models this is done by including the projected cost decline, associated with an expected growth in cumulative capacity, in the expectations and thus in the investment decisions of actors. POLES actually included R&D spending as an explicit driver of learning.

The 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 of the NLP problem, the 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 solution time and the success to find 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, and therefore it is a limitation of modelling endogenous learning with perfect foresight.

The interaction between different clusters in terms of lock-in, lock-out, path-dependency, and spill-over 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.

## 4.3 Results from modelling endogenous technical change/learning

### 4.3.1 General Conclusions

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) show 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.

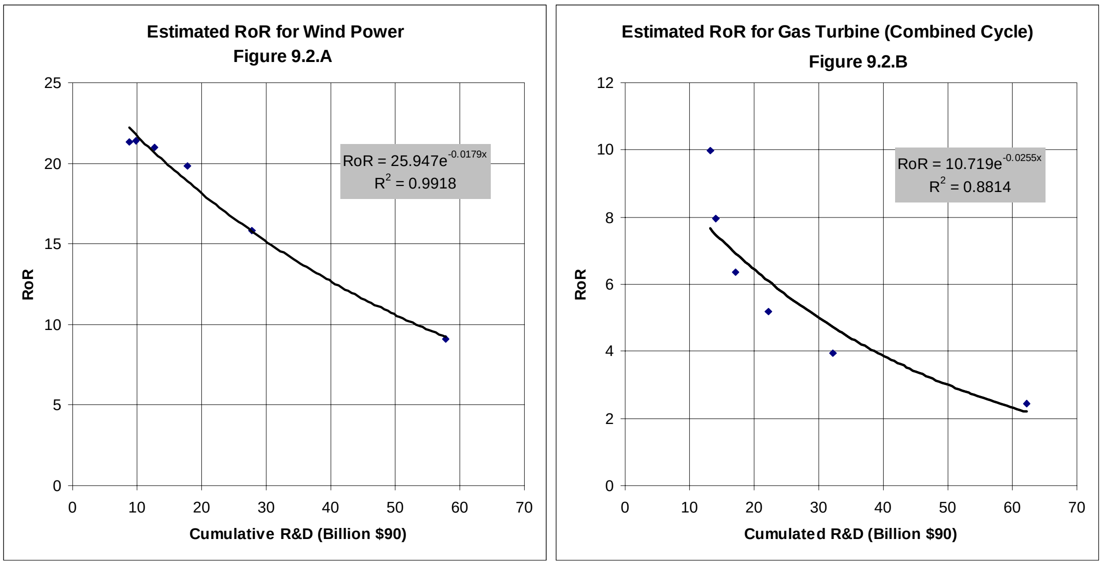
Several types of RTD interventions can accelerate the market penetration of new technologies. The directions into which such interventions might lead have been illustrated in some of the experiments.

The results of the Post-Kyoto analyses indicate that estimates of the cost of $CO_2$ reduction will be decreased if the concept of endogenous technology learning is adopted. Policy measures aiming at $CO_2$ 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.

### 4.3.2 POLES experiments

The implementation of the R&D module in the POLES model took right from the beginning an experimental character. This was to a large extent due to data problems. Runs of the POLES model permitted the quantification of rate-of-return of R&D funding for each technology, as illustrated in Figure 5.

Figure 5: Approximated rate of return of R&D investment in gas turbine in combined cycle and wind power (results from POLES)



Few lock-in instances were identified despite the inclusion of full learning mechanisms and they proved relatively easy to rectify. This positive result was obtained primarily due to the incorporation of private R&D agents displaying contrasting risk aversion stances. High risk takers have an important role to play in ensuring that the system responds rapidly to “shocks” while the risk averse tend to keep the options open thus maintaining the system’s capacity to respond to further and ultimately contradictory circumstances.

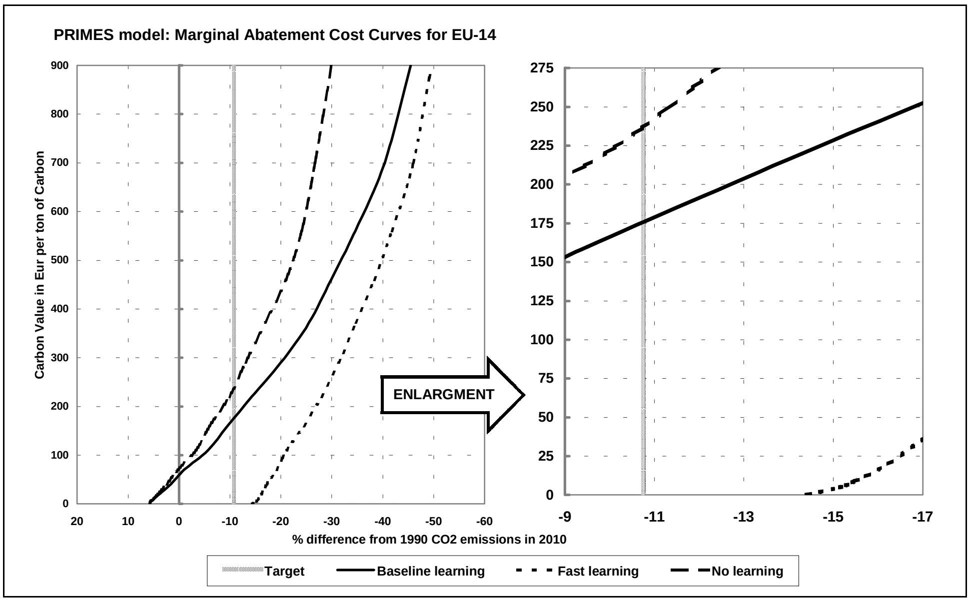
The addition of endogenous learning has modified the system’s response to greenhouse gas emission limitations by introducing additional elements of flexibility. This has resulted in significant reductions in the costs of satisfying emission constraints and suggests that most models which ignore the endogenous character of technical change will tend to overestimate them (in the case of POLES this overestimation was of the order of about one third).

The enlarged version of the model proved capable of effecting meaningful public R&D strategy exercises in the sense that budget re-allocations tended to achieve at least partially their stated objectives. This occurred despite the fact that private R&D response not only remained independent of public R&D decisions but even to a certain extent reacted in a counter fashion (“crowding out” effects).

### 4.3.3 PRIMES experiments

The implementation of endogenous learning within PRIMES, in a manner very different from that of POLES, also confirms its technical feasibility, at least in a partial way, and its significant impact on the results for the EU. The introduction of the carbon value of the post-Kyoto scenario in the 'no-learning' and the 'fast learning' scenarios leads to an increase by 30 $MtCO_2$ and a decrease by 166 $MtCO_{2,}$ respectively for the two scenarios of $CO_2$ emissions in 2030 when compared to the post-Kyoto scenario. In order to achieve the same emission reduction as in post-Kyoto scenario, i.e. -5.3% from 1990 levels of $CO_2$ emissions, a carbon value of 190 €90 per ton of carbon avoided should be introduced in the 'no-learning' case and of 117 €90 per ton of carbon avoided in the 'fast learning' case.

Figure 6: Marginal abatement cost curves for different regimes of technology acceptance, 2010

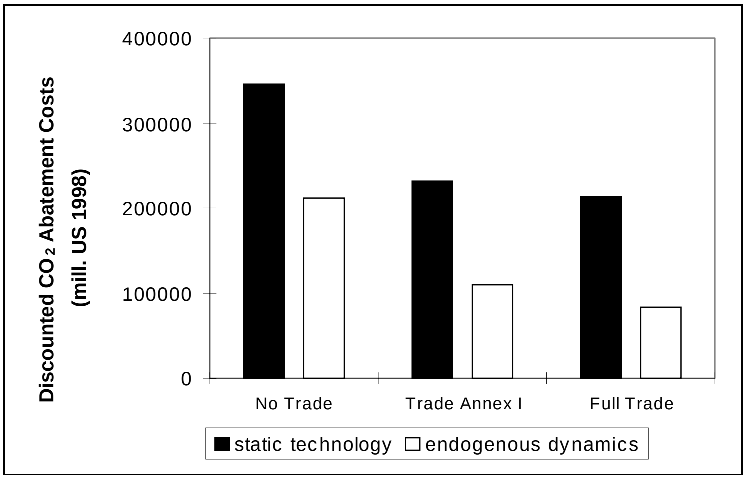


The energy system cost within the EU for achieving the post-Kyoto target reaches 17230 MEur'90, or 0.15% of EU gross domestic product in 2030. The corresponding costs in the 'no-learning' and the 'fast learning' cases are 19400 MEur'90 and 7315 MEur'90, respectively. The gain resulting from incorporating endogenous learning in the post-Kyoto scenario is 2180 MEur'90, or 0.02% of EU gross domestic product. The potential gain under the 'fast learning' assumption, when compared to the 'baseline learning' post-Kyoto scenario, reaches 9915 MEur'90, or 0.09% of EU gross domestic product.

### 4.3.4 ERIS experiments

The analysis of Kyoto-for-ever scenarios indicates that a significant departure from carbon intensive generation options is required to fulfil the $CO_2$ emission targets. Otherwise, global emissions from electricity systems will continue to grow substantially. With an endogenous representation of technology dynamics, early up-front investments are made to stimulate the necessary technological progress of emerging low -or free- carbon generation options, which are then able to play an active role in the mitigation strategy. When uncertainty in emission reduction commitments is considered, the results point also in the direction of undertaking early abatement action as a preparation for future contingencies. This early action stimulates technological learning that proves beneficial in terms of both lower costs and emissions in the long run.

Figure 7: Comparison of discounted CO2 abatement costs. Kyoto-for-ever scenario



The possibility of trading emission permits, either between Annex I regions or extending the trade to non Annex I regions, will allow some regions to undertake less radical changes in their electricity sectors than what would be required otherwise. Nonetheless, trade does not rule out action in the regions with commitments. However, trade may provide incentives for the penetration of emerging learning technologies in different regions, stimulating accumulation of experience with them, and thus contributing to the progress along their learning curves towards long run cost competitiveness.

Competition against well established generation technologies will not be easy for emerging, less carbon intensive alternatives. If they are to play a significant role in future electricity generation markets, emerging technologies will require investments, both in R&D and niche markets, to foster their development. Technology policy instruments may also be required to provide specific incentives for the production of electricity from new technologies. Therefore, their successful introduction requires a strategy that promotes innovation and learning at multiple technological, social and institutional levels.

### 4.3.5 MARKAL experiments

The results from the new runs with the Western European MARKAL model that features endogenous technology learning again confirm that $CO_2$ reduction policy, progress ratios applied, and user-defined bounds are very influential on the outcomes and technology prospects.

The use of clusters of technologies will prevent the underestimation of the induced technological progress by the learning-by-doing mechanism. This coupling of the experience of technologies that share important common learning components is a pre-requisite for obtaining consistent results. One of the specific advantages is that experience gained in rather different markets is combined, e.g. as is shown for the fuel cell technologies.

The results indicate that several emerging technologies show good prospects in Post-Kyoto scenarios in the longer run. Robust conclusions cannot be drawn at this stage, as considerable uncertainties remain that warrant further study. With this caveat in mind, the following specific technologies emerge positively in the post-Kyoto time frame: wind turbines, gas turbines (using gas and/or gasified biomass), nuclear (subject to assumed expansion limits) and fuel cells. Solar PV cells for power generation are particularly sensitive to assumptions with regard to progress ratios and other relevant learning parameters, not just of the PV systems themselves but also of their direct competitors. Hence unambiguous results are not found for this technology.

The figures below illustrate that according to the MARKAL analysis the consideration of endogenous learning is important. The figures show the penetration of some energy technologies and the cost of meeting a CO2 target comparing a learning case (ETL) with a non-learning one (NETL). The technologies shown are: GF gasifier, GT gas turbines, WT wind turbines. Similar results are produced for a variety of technologies, clusters and assumptions on their development.

Figure 8: Cumulative capacity (CCAP) of key technologies, CO2, ETL vs. NETL

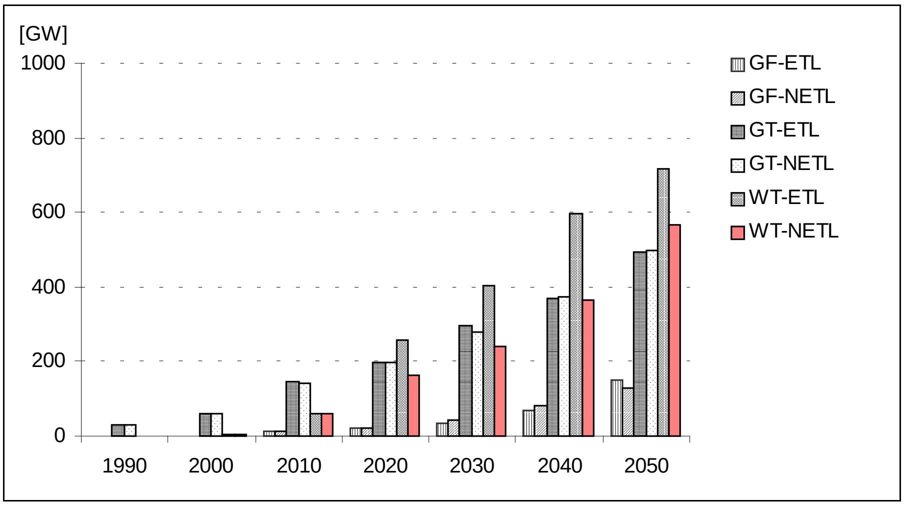
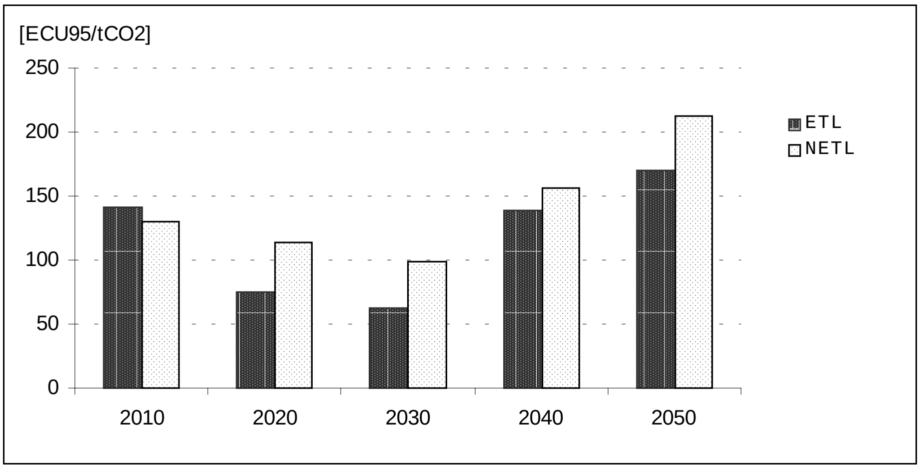


Figure 9: Marginal cost of CO2 reduction, ETL vs. NETL



## 4.4 Conclusions for RTD Strategy

Action to protect the global climate has short-term implications for policy even though global warming is a very long-term issue. One reason for this is that technological strategies for greenhouse gas mitigation have long lead times. If action aiming at GHG mitigation does not begin early enough, technological progress may take off into undesirable directions. Worse, technological progress through “learning by doing” might lock the European energy system into an environmentally harmful path instead of steadily increasing the competitiveness of low-carbon technologies.

The introduction of endogenous technology progress, particularly when combining dynamics and endogenous learning, even at the simple reference to capital costs, may have dramatic consequences for the derived policy recommendations for global warming. Depending on the numerical magnitude of learning, the policy perspective for $CO_2$ emission reduction will be highly more optimistic and less costing than in traditional studies that do not consider endogenous technology progress. The degree of overestimation of the cost of satisfying emissions constraints as a result of not taking into account endogenous learning could be of the order of one third.

Similarly, the stochastic aspects are very important for policy analysis. The consideration of hedging attitudes in the presence of technological learning implies different priorities for early actions, than in traditional analysis. A portfolio type of decision for technology investment can be generated when stochastics are considered both for global warming and technological learning.

An important policy aspect is the possible existence of niche markets, where a competitive edge for new technologies can be obtained at limited efforts, e.g. in the case of fuel cell applications in the MARKAL runs. In this case a niche market for vans offer possibilities to stimulate early deployment in a particularly cost-effective way, with subsequent deployment in other markets (buses and even in the stationary power generation sector). The potential relevance of demonstration and dissemination programs focused on suitable technology/niche market combinations are thereby illustrated.

# 5. Other issues examined

## 5.1 Scope of work

While a main concern of this report is the impact of the endogenisation of technical change on global climate, it is clear that a number of other policy concerns and developments are likely to play a key role over the next 30 years in affecting energy trends. Thus, the project examined the impact two policies related to energy could have on the penetration of new technologies: a) a transport policy aiming at reducing the air pollution linked to transport and b) an energy policy aiming at promoting the use of renewables and the competitiveness of European’s renewables industry.

On the first issue, current EU policy proposals regarding transport air quality targets were evaluated and compared with a policy combining this policy proposal with a tax reform aiming at more neutrality between the fuels in terms of the generated damage. The analysis was done using the PRIMES transport model in combination with the PRIMES refinery model in order to take into account both the demand supply impact of these policies.

On the second issue, the project used the SAFIRE model in order to examine how an EU policy promoting renewable energy can induce a higher penetration of this type of energy and what could be the impact on employment, Europe’s energy self sufficiency and its competitiveness in that domain on the world markets. This study was complemented by case studies assessing four individual technologies: wind, photovoltaics, biomass electricity and solar thermal heating, with special emphasis on the Danish experience with wind energy.

It should be noted that a significant part of the work carried out in the context of TEEM has used extensively the concept of learning curves. A large amount of work was carried out in order to collect relevant data in a standardised way and to estimate statistically some key parameters. In general, while learning curves have proved to be a valuable tool for the endogenisation of learning, there are limitations in their application due to weaknesses in the available data and to the consequent uncertainty on the stability of the relationships that they represent.

## 5.2 Renewable Energy

The European Union is poised to be the world leader in a number of renewable technologies. This is partly because Europe's internal market is providing the springboard for developing a robust, internationally competitive industry. In the case of wind and PV, the EU is already at the forefront of renewable technology in a rapidly growing world market. The creation and maintenance of such a powerful market position will be difficult in the current competitive environment. It is therefore important that, if Europe wishes to maintain its competitive position, the European Union and Member State governments actively support renewable energy through industry, finance and the consumer to enable European organisations to be key players in the global market.

With such support and with a potential renewable energy market growing by a factor of ten in the medium term, this is an ideal opportunity for Europe to obtain a significant market presence. This, in turn, will have internal benefits in terms of employment, reduced import dependency, increased technology export opportunities and improved energy self sufficiency.

## 5.3 Transportation impact on air quality

The EU policy measures related to fuel quality and emission standards for transport technologies will have a major impact on the emissions from road transport responsible for regional damages such as SO2, NOx, VOC and PM. Their impact on $CO_2$ emissions originating from the transportation sector is more limited: -7% in 2030 compared to the reference, but still 75% higher than in 1995. The cost increase imposed by these measures is insufficient to allow for a significant penetration of new fuels and technologies in the transportation sector.

Combining the EU policy with a more fuel neutral tax policy, in which existing excise taxes are replaced by a road tax and pollutant taxes, will reduce further the environmental damage from transport. This is mostly obtained through a stronger reduction of the freight transport volume and a substitution from diesel to gasoline compared to the EU policy scenario. This measure does not increase significantly the potential market for alternative fuels like methanol and ethanol or electric cars; their share can reach 10% in some countries, but it remains generally more limited. It is clear that the EU policy measures have reduced the benefits in terms of environmental damages that can be obtained from alternative fuels and technologies when such a fuel neutral tax policy is introduced. In terms of $CO_2$, the new taxes induce a doubling of the reduction of $CO_2$ emissions compared to the one obtained with the EU policy measures, but the emissions are still 65% higher in 2030 than in 1995. This seems to indicate that the marginal cost of $CO_2$ reduction in the transport sector remains very high compared to the damage figure used in this study.

## 6. Data Issues and Future research

Further research is required in the study of both the magnitude of the externalities generated by technological spillovers and the appropriate levels, orientations, and processes for public R&D. In view of theoretical difficulties involved in RTD funding strategies and relationships with technological progress, simplified mechanisms will need to be explored and tested thoroughly in modelling experiments.

The scale at which learning takes place (global, regional) will certainly affect the development technology. The spatial dimension of technological learning and the possibilities of learning "spill-over" are aspects that deserve further investigation.

The ERIS results show that the consideration of uncertain learning rates may drive the model to follow a more prudent and gradual path of investments in learning technologies. Other uncertainties have also an impact, stimulating or delaying technological learning. Since uncertainty is, together with learning, at the core of the endogenous mechanisms of technological change, future work should also be devoted to a more thorough exploration of the effects of uncertainty both on learning rates and other driving forces such as demands and environmental constraints.

An important conclusion is that the estimation of the data required for endogenising learning is not straightforward. This is due to the lack of availability of adequate statistics, the more stringent requirements for the accuracy of some data (e.g. the cumulative capacity and initial costs in the starting period) and the large sensitivity of the results found for these new 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 better 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.

# 7. Exploitation plans and anticipated benefits

A summary of exploitable results is given below.

## 7.1 Models

Energy models maintained and expanded to include endogenous technology progress mechanisms:

- POLES (World energy)
- PRIMES (EU energy)
- ERIS (new world power generation)
- MARKAL (for Western Europe)

Other energy models maintained and used:

- SAFIRE (EU energy technologies)
- MESSAGE (World)

## 7.2 Model simulations and scenarios

Two families of model scenarios to 2030 have been constructed:

- Baseline scenarios for the EU and World
- Series of CO2 target scenarios for the EU and World

The above scenarios are available for different assumptions regarding technology progress:

- Exogenous technology progress
- Exogenous but accelerated technology progress (technology stories)
- Endogenous (induced) technology progress.

## 7.3 New Data

New data have been collected for energy technologies and statistically exploited in the project. The data concerned:

- Technical-economic data for demand and supply energy technologies
- Historical time-series for key new energy technologies
- R&D spending

All these data have been organised in a database software called E3TDB and diffused on a CD-ROM.