SAPIENT

Systems Analysis for Progress and Innovation in Energy Technologies

SYSTEMS ANALYSIS FOR PROGRESS AND INNOVATION IN ENERGY TECHNOLOGIES
Research Project DG RES, 5th Framework Programme
Contract N° ENG2-CT1999-00003
Partners: ICCS.NTUA, CNRS.IEPE, ECN, IPTS, KUL, PSI, IER, IIASA

–FINAL TECHNICAL REPORT–

Coordinated by: ICCS-NTUA (N. Kouvaritakis)

with contributions by:

P. Capros, V. Panos, K. Manolitzas, L. Mantzos and T. Zaxariadis, ICCS.NTUA (Greece)

P. Criqui and S. Mima, CNRS-IEPE (France)

S. Kypreos and O. Bahn, PSI.CH, (Switzerland)

L. Schrattenholzer, G. Klaassen, A. Miketa, K. Riahi and L. Barreto, IIASA.ECS (Austria)

M. Blesl, A. Das, U. Fahl and U. Remme, IER (Germany)

A. Soria and J.C. Ciscar Martinez, JRC-IPTS (Spain)

G.J. Schaeffer, A.J. Seebregts, M.A.P.C. de Feber and K.E.L. Smekens, ECN (The Netherlands)

M. Magdalinos, AUEB (Greece)

Athens, February 2005

SAPIENT

Systems Analysis for Progress and Innovation
in Energy Technologies

SYSTEMS ANALYSIS FOR PROGRESS AND
INNOVATION IN ENERGY TECHNOLOGIES
Research Project DG RES, 5th Framework Programme
Contract N° ENG2-CT1999-00003
Partners: ICCS.NTUA, CNRS.IEPE, ECN, IPTS, KUL, PSI, IER, IIASA

Part 1

–*Publishable Final Report*–

Edited by: N. Kouvaritakis, ICCS-NTUA (Greece)
E. Argiri, ICCS-NTUA (Greece)

Athens, February 2005

–Executive Publishable Summary–

EXECUTIVE PUBLISHABLE SUMMARY

1. Objectives

The objective of the SAPIENT project has been to consolidate and carry forward recent advancements of research in energy systems analysis regarding the dynamics of technical change. More specifically the project has focused on the role of R&D in accelerating technical progress in order to promote given energy, environment and economic policy objectives. The main ambition has been to develop methodologies that can be used for performing quantifiable model based R&D strategy elaboration. Such strategy evolves in a context of multiple objectives including both traditional and sustainable development concerns and must take into account a wide set of uncertainties. Such uncertainties arise not only from the inability to predict the impact of R&D action on the technical and economic performance of specific technologies but also from a host of other factors that may influence such performance as well as future economic and policy conditions .Special attention has been given in establishing quantified synergies and conflicts between different objectives and policy actions.

2. Description of Work

Work in the SAPIENT project has been structured around building the capability for carrying out integrated R&D policy exploration and more specifically in providing the essential input for the ISPA meta-model that has been used for this purpose. Along this main axis many data collection, estimation, model building and scenario evaluation tasks have been performed that apart from serving the main objective of the project have provided useful insights on the dynamics of technical change in the power generation sector in a period of increasing sustainability concerns. Early in the project a technology dynamics database was created containing time series on economic characteristics, capacity installation, as well as public and business R&D directed at the improvement of 22 key power technologies. This database is unique in its kind especially with regard to R&D estimates derived from the number of patents obtained on given technologies. The database provided data for the statistical estimation of a technological progress sub-model incorporating learning attributed to research effort and learning arising from the experience gained through technology take-up. Since all existing models that participate in the project are essentially deterministic in character and the R&D policy exploration involves dealing with risk management, a complete stochastic world energy model (PROMETHEUS) has been constructed in order to provide probability distributions of the impact of R&D directed at specific technologies on key energy and environment indicators. Using mostly statistical analysis but also expert assessments or opinions to derive the magnitude and interconnection of basic uncertainties PROMETHEUS through its structure produces joint distributions for all its output. It strives to ensure that no uncertainty is underestimated and can therefore be applied over a wide range of risk analysis problems. Variants of the learning mechanism developed within SAPIENT were introduced in PROMETHEUS, the world simulation model POLES and the perfect foresight models: MARKAL and TIMES (Europe), MESSAGE (world, very long term), ERIS and MERGE-ETL (containing feedbacks to the economy). Implementation in perfect foresight models presented specific challenges in overcoming lock-in effects. After some harmonisation of assumptions (including future climate change policy), model generated Baseline and R&D policy scenarios have been developed and compared. A set of common policy quantitative target indicators including profitability, CO2 reduction, security of supply and energy costs to consumers have been defined and models have been used to measure the impact of R&D on them on a technology by technology basis. Results from these exercises were used in constructing ISPA which takes the form of an optimisation tool maximising the probability that a given threshold on a policy objective is attained while specifying minimum probabilities of attaining thresholds on other policy objectives. ISPA has been used for R&D policy exploration involving proxy decision makers. Naturally the portfolios vary depending on the priority given to the different policy objectives but they are generally diversified with a core of candidates attracting R&D funding under most conditions. Some of the choices would have been difficult to be guessed at in the absence of the tool but the whole process provides robust and transparent justification for them.

3. Exploitation Plans

The methodology developed within the SAPIENT project has wide potential applications in R&D strategy elaboration and can be extended to cover more technologies (beyond the power generation sector) and encompass a wider range of policy objectives. It can also be extended to domains beyond energy R&D policy exploration to address optimal policy exploration in the presence of multiple objectives and uncertain policy impacts. PROMETHEUS, a new model developed in the project is available for the risk assessment of scenarios and policies affecting the World energy system. The SAPIENT project has also delivered advanced versions for all participating models that incorporate endogenous technology progress and are capable of further R&D scenario elaboration but also a more complete and realistic representation of energy systems opening the way for improved energy systems analysis.

–Publishable Synthesis Report –

Table of Contents

Publishable Synthesis Report

I. Introduction

The Sapient project addresses the general issue of energy systems analysis by considering key driving forces that induce energy technology improvements and by evaluating the most relevant environmental, energy and economic implications. The research is aimed at the developing of a model based analysis on energy technology dynamics and their changes as induced by policy. For this purpose, the project uses existing tools, namely the major European large-scale energy system models and in particular their versions that incorporate energy technology progress as an endogenous process within the models. The project also aims at constructing a model-integrating decision-oriented tool to evaluate R&D policy priorities under uncertainty. The systems analysis covers the European Union and the World, addresses global warming policy issues in the presence of liberalised energy markets and constructs scenarios putting forward the role of induced technology process.

The work presented in SAPIENT constitutes an ambitious extension of the TEEM project already completed within the Fifth Framework Programme. The TEEM project's main concern was the dynamics of technological change taking as a specific paradigm power generating equipment. Special emphasis was given to learning processes and pre-eminently the process of "learning by doing". Such processes were extensively analysed using large scale energy models of widely differing structures and philosophies. Building on the insights gained in TEEM the major ambition of the SAPIENT project was to extend and synthesise technology dynamics results in order to render them useful for actual R&D budgeting policy exploration. The challenge for SAPIENT was to re-visit the energy-environment-technology systems analysis (for Europe and the World), so as to attempt to estimate the value of achieving accelerated technological progress in the fields of energy demand and supply and introduce the policy instruments that could generate such process.

It is widely recognised that technological improvement induces benefits for the economy, consequently Research and Development (R&D) programmes and policies are highly important for economic growth. In recent years there has been an increased awareness that policy strategies as well as overall economic and societal objectives can accelerate the rate of technological improvement. Technological improvement in its turn exhibits strong environmental externalities, especially as regards the energy sector. In this context, there has been increased awareness that policy strategies targeting technological development are among the most effective means for reconciling economic ambitions with global environmental and ecological objectives. However, energy systems analysis and models have mostly neglected this causal relationship, overlooking that policy and economics have implications upon research, development and diffusion of new technologies. This omission arises 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. Recent research in energy systems analysis provides evidence of a new empirical approach to this problem. The corresponding preliminary analysis shows that energy and environmental (especially climate change) strategies have to be substantially re-considered when evaluated in the presence of induced technology progress possibilities.

One of the major objectives of the SAPIENT project was to assist and further elaborate this advancement of research in energy systems analysis. The aim was to elaborate a full-scale assessment of energy technology strategy as a means of efficiently addressing energy and environment policy objectives, taking into consideration that these policy instruments and set of objectives will drive (accelerate or obstruct) the energy technology process. The project delivers a rich set of key energy technologies in the frame of the interplay between energy and RTD policy, policy instruments, social targets (e.g. global warming, competitiveness etc.) and technological improvement. Moreover, the project goes one step further to provide results on RTD priority issues, portfolio allocation, innovation policy, energy and emission scenario developments (for the EU and the World), analytical and quantified results which illustrate the mechanisms of induced technological progress. Ultimately, the analysis on the strategy for the post-Kyoto period in the presence of induced technological improvement is a major contribution from SAPIENT.

II. Objectives and Strategic Aspects

The liberalisation of the European and World economies that has been gathering pace in the last two decades has been backed by a political will to enhance efficiency, widen choices and reduce administrative obstacles through increased decentralisation of decision making. This ongoing process has intrinsically been accompanied by a shift in the scope and nature of public sector instruments in pursuit of societal policy objectives. Direct intervention by public authorities in order to achieve specific results is becoming less and less attractive and is not considered desirable to the extent that it may hinder the above-mentioned evolution and may pose problems of transparency as well as potentially create distortions. Public instruments have therefore tended to become increasingly indirect and less and less interventionist. A domain where plenty of scope for such indirect public actions in pursuit of broader policies is public budgeting R&D, especially where the aims are longer term and the benefits are likely to accrue to a wide spectrum of stakeholders.

SAPIENT is an applied research project specifically aimed at analysing the mechanisms through which R&D actions translate into results in terms of specific objectives, and at exploring the R&D strategies in pursuit of such objectives. Although it concentrates on energy technologies and more specifically on future technological options in the power generating sector the methodology developed has the potential for applications in a much wider context encompassing all kinds of R&D strategy considerations.

The project progressed on the fronts of establishing the mechanisms of transmission from R&D action to technological improvement along certain axes and in view of specific objectives.

The extensive utilisation of existent detailed models which describe the energy system in its considerable complexity provides a consistent framework for the simulation of the impact of R&D actions. In addition to this aspect which utilises and extends modelling work that has been carried out over recent years, partly financed through EU research programmes, the present project makes an attempt to develop tools that synthesise these mechanisms and provide instruments that serve as compact vehicles to the performing of real public R&D exploration exercises.

The methodology recognises two important characteristics of the public R&D budgeting process namely that:

- The aims of public policy are multiple and different R&D choices may serve them differentially;
- The outcome of R&D action in terms of these objectives is not deterministic i.e. there are risks involved all along the causality chain from the impact of R&D funding action on the technical and economic characteristics of specific technologies to their up-take in the market and all the way to the generation of a desirable impact on the policy objectives themselves.

In this way the policy exercises performed involve hedging allowing for different risk stances as well as alternative rankings of the different objectives themselves explored through the use of pay-offs between them.

The project covers the evaluation of numerous important policy objectives. First, the market impact per technology is considered (for around 20 technologies) approximated by the value of additional consumer surplus arising from the R&D action or the increase in volume sales triggered by technological cost reduction. The cost of meeting a given CO_2 target is also examined utilising measures such as greenhouse gas emissions or other proxies, e.g. cumulative world emissions. Total energy cost for the EU final energy consumer (firm and household) is also measured. The same cost is separately estimated for the consumer in developing countries, measured in the same manner as for the equivalent EU objective. Finally the

Security of Supply is estimated as the deviation of hydrocarbon prices over a certain “reasonable” threshold.

Typically, energy scenarios analysed with energy system models assume that characteristics of technologies can change overtime. The development of these characteristics is treated as a function of dedicated RTD and market deployment under varying external conditions. As a result, the assessments of future trajectories of energy systems should also take into account context-specific (i.e. induced) technological progress. This can be seen as a reflection on technology dynamics (learning). Internally consistent frameworks incorporate links with technological change, including learning rates and technology maturing costs. However the trend is often assumed to be exogenous to the energy system analysis model. This applies to technology cost indicators like the specific investment cost and to performance indicators, e.g. the efficiency of energy technologies.

Endogenous technological learning has been recently shown to be a very promising new feature in energy system models. A learning or experience curve describes the specific (investment) cost as a function of the cumulative capacity for a given technology. It reflects the fact that the technologies may experience declining costs as a result of their increasing adoption due to the accumulation of knowledge through, among others, the processes of learning by doing and learning by research.

In view of this challenge, and in an effort to capture this promising new feature, SAPIENT sets a series of ambitious scientific objectives, which constitute a clear advancement in the domain of energy systems analysis and modelling. Key among these objectives are:

- The update of existing data as well as the creation (by direct or indirect means) of a credible data set to estimate the relationships that link energy technology improvement with energy system investment and public and private R&D spending. Specific, data was collected covering costs, capacity installation, public and private R&D expenditure for the most important present and future (to 2030) technological options for the power generating sector.
- The estimation and establishment of a consensus on the relative importance of “learning by research” (R&D) and “learning by doing” (experience) on a technology by technology basis. Most estimations and the overwhelming volume of model applications existing in the literature concern one factor learning curves (namely learning by experience) which however have limited use in R&D policy applications.
- These two factor learning relations were implemented in large models including perfect foresight optimisation models with all the attendant difficulties of instability of results, lock-in and crowding out effects as well as the presence of local optima which necessitated special algorithmic treatment.
- The measurement of risk associated with energy developments and more specifically risks concerning the impact of R&D actions in specific objectives. It has been clear that the interconnection of these risks (co-variances) should be measured as well if credible policy exercises were to be performed.
- The development of a dedicated decision support tool that can explore R&D priorities in a quest for minimising risks, hedging against uncertainty and maximising the economic, environmental and energy policy benefits from expected technological improvement.
- The development of a small integrating model which incorporates the endogenous technology learning in an energy and economic growth system seeking maximising welfare in the presence of uncertainty and risk aversion.
- The construction of complete energy scenarios for the EU and the World with models that incorporate the induced technology progress mechanisms and evaluate, in this context, the interplay between policy instruments, market liberalisation, global warming and technology improvement.

III. Scientific and technical description of the results

The primary topic of the SAPIENT project has been the issue of incorporating technology learning endogenously in energy models and trying to determine the impact of public R&D on this learning process. The challenges faced to ensure the credibility of this process have been very considerable throughout the project. The agenda of research constituted from the very beginning a clear advancement in the domain of energy systems analysis and modelling. The following sections report on the tasks undertaken, within the SAPIENT project, to specify and develop models that include endogenous energy technology evolution mechanisms. Technology progress is specified in a way that represents dynamic effects of RTD policy, including innovation funding, patents, diffusion of technologies and international co-operation. The impact of related issues such as learning by doing, learning by research, economies of scale and hedging strategies is also examined.

1. Technology Improvement Dynamics Database

The compilation of a reliable model data set has received considerable effort and amount of time from the SAPIENT team. A major objective was to check and harmonize technical-economic data on energy technologies, including information on their purchasing cost, their technical/economic life duration, energy efficiency performance and availability, in order to ensure comparability of the subsequent results. The task concerned updating the existing E3TBD database (resulting from previous Joule projects TEEM and Climate Technology Strategy) and disseminating it for use and calibration in the different models participating in the analysis. Furthermore historical information on the improvements of at least some of these technical-economic characteristics of energy technologies had to be collected and checked for overall consistency, insomuch as these improvements could be attributed to a learning or experience process associated to the use of these technologies.

To this extent, statistical information on public and private expenditures in R&D activities for electricity generation technologies had to be collected in a way as to be able to attribute, albeit approximately, specific expenditures to the different technologies concerned.

The resulting major accomplishment of the SAPIENT project was the creation of a common database structure called TIDDB (Database on Technology Improvement Dynamics for Power Generation Technologies). The innovation of the TID database lies upon the provision of consistent data in order to assess the drivers and inducement factors in the dynamics of energy technologies. This historical database serves both as a suitable sample for estimation and an appropriate starting point for model runs. It assists the identification of not only capacity installation but also cost improvements and, above all, the attributing of private and public R&D effort to specific technological options. A variety of sources had to be utilised in order to cover this wide spectrum of data required. The information acquired was then processed using innovative methods including concepts such as patent applications.

The main vehicle of transmission from a specific R&D action to a desirable effect is the Two Factor Learning Curve (TFLC). At exploring the role of R&D and energy policy, the concept of learning/experience curve was employed. To further improve the approach and increase the reliability of the “learning by doing” and “learning by research” estimates, the database was enriched with data on the cost of key power generation technologies and on the key explanatory two factor learning curve variables, i.e. cumulative capacities, cumulative government energy R&D (GERD) and cumulative business energy R&D (BERD).

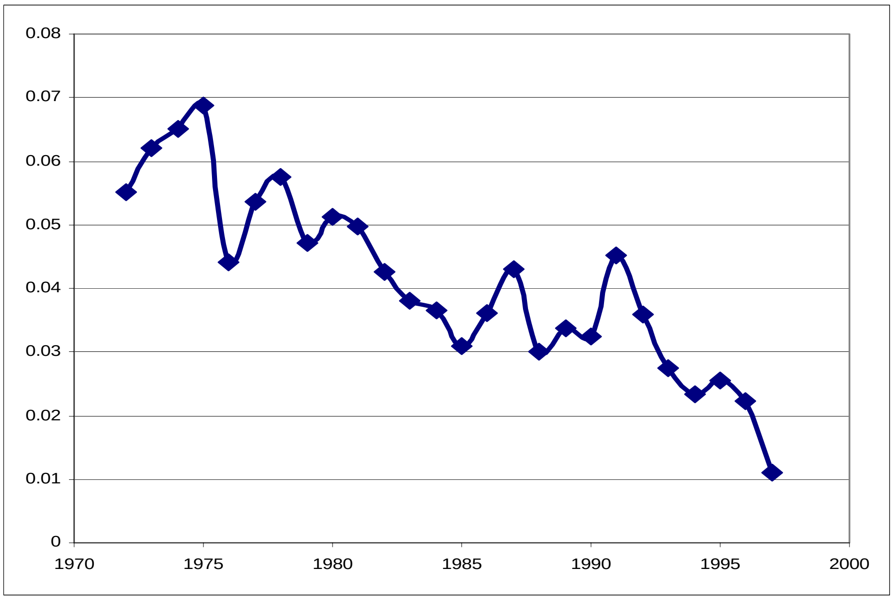
The final synthesis of the database presents analytical data for six technology characterisation factors with respect to 23 power generation technologies, for the years 1971-1997. The factors covered are:

- Installed capacities by world region;
- Sales of the different power plants;
- Public R&D by category;
- Private R&D for a panel of 14 power generation equipment companies;
- Patents requests by technology and
- Costs by technology;

This unique information set represents the state of the art of the TIDdb database for the study and econometric estimate of the Two Factor Learning Curves for some key technologies. The information is arranged in separate but inter-connected spreadsheets that allow for transparency in the passage from detailed primary to secondary data. The procedure has followed innovative methodology particularly in connection to deriving some indicators for private R&D by technology combining company specific information with patent applications data. This information set is potentially very useful for international organisations dealing with technology and environmental issues as well as the main European companies in the power generation equipment and electricity sectors.

A preliminary analysis of the data set in itself can provide some key insights on the global trend in the energy sector as well as the economic/technical behaviour of key energy technologies over time. To begin with, the analysis of world power generation capacities shows a linear type growth in the past twenty years, with a marked slowdown in growth in the last years of the period considered (1991-1997). The yearly average growth rate falls from 6% per annum (pa) in the early seventies to less than 2% pa in the late nineties; this is mainly due to the decline in the share of oil-based power generation capacities during the whole period considered, but in particular in the late seventies after the two oil shocks. This impact however is moderated by the marked increase in nuclear share and in gas-based power plants.

Figure 1: World power generation capacities, annual growth rate



Regional dynamics also have an explanatory impact on this trend. The OECD region presents a continuous slowdown in the expansion of power plant capacities, while the growth pattern in this region is not even linear. However, this negative trend is compensated by data coming from Economies in Transition (EIT) and Asian countries, as the rate of growth in power generation capacities in these regions appears increasing, the fastest being the rate of 8%pa between 1971-1997, achieved in the Asia region. Still, the Rest of the World regions contribute to the initial negative trend, as the increase in generation capacities slows down significantly between the beginning and the end of the period, with average growth rates of 10%pa in the seventies but only 4% on average in the nineties.

Total World power generation sales in MWe increase moderately during the period considered, from 80 Gwe/yr in the early seventies to 120 Gwe/yr in the late nineties, the slow-down by the end of the period being partly due to evolutions in the EIT. The OECD region which accounted initially for the three fourths of the market drops its share to about one half since the mid-eighties. Turning to the total power plant sales in dollars, their value appears to remain relatively stable overtime, except in the very last years considered. Interestingly however, the OECD share is once again decreasing from two-thirds to one-third of the total sales.

This evolution of the total sales indeed results from the combined effect of the variations in sales in volume and of the price/cost of the technologies. The latter in turn depends on the cost dynamics proper to each technology and on a technology-mix effect (some technologies presenting structurally higher costs, such as hydro or nuclear). This is illustrated in the average MWe cost which shows only a slight decline in the mid-eighties, with the development of nuclear power plants, but a marked decline later on, from an average 1 500 to 1 000 $/kWe. This corresponds to the phase of development of the new gas-based capacities, which are both investment-saving and subject to rapid technological progress.

Turning to Government Energy R&D, statistical data coming from the IEA demonstrate drastic variability over time. Total GERD volume first rockets from 8 G$ in 1974 to 16 G$ in 1980 (during the second oil shock), down again to 8 G$ during most of the nineties. Power generation technologies account for approximately three-fourths of this total R&D, with nuclear technologies representing the lion’s share, namely three-fourths of the power technologies.

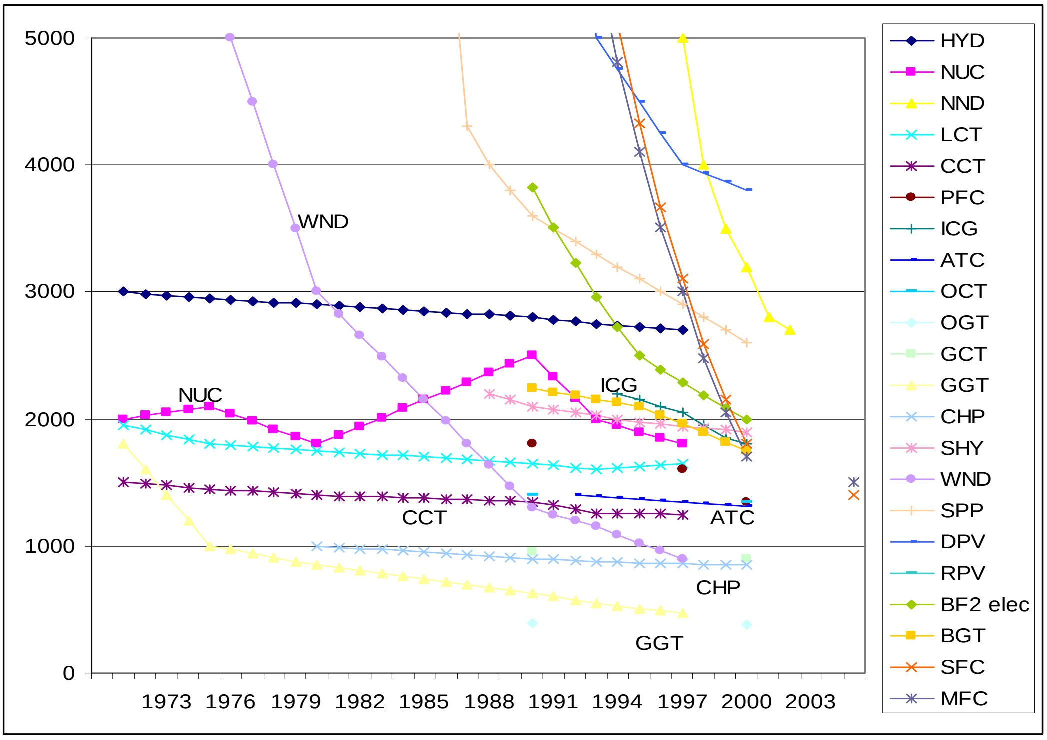
The full disaggregation of net cumulative GERD among conventional, new and renewable technologies further confirms the predominance of nuclear technologies, whereas all other technologies appear with a net cumulative R&D, inferior to 5 G$, i.e. at least one order of magnitude below nuclear technologies. As far as renewable technologies are concerned, PV technologies clearly benefit of the highest R&D stock followed by wind, while the solar thermal power plant technology shows a marked slowdown since the mid-eighties. The stabilisation of the R&D stock from government for fuel-cell vehicle may be explained by the fact that, since the mid nineties, large programmes have been launched by the industry. This case however poses the more general problem of the “technological clusters” in which R&D followed by progress in one technology may benefit to other technologies through the direct improvements in common components and methods or through technological “spillovers”.

Patents for power generation technologies peaked to 8000 patents per year in the OECD countries between 1980 and 1985, compared to the low level of 2000 patents per year between 1970 and 1975. Ever since the annual number is stable at 5000 patents but shows a marked decrease in the last two years of observation. As for the number of patents by technology, nuclear technologies dominate in the seventies, photovoltaics in the early eighties, while gas powered technologies present the highest share of total patents in the nineties.

Business Energy R&D can provide an additional perspective, as it encompasses on-going R&D for mature technologies that, in many cases, does not translate into patenting. The resulting picture is to some extent different than the one obtained with the pure patent indicator; nuclear is indeed still dominant until the mid-eighties, but later on Gas turbines in Combined Cycle appear as the leading technology, with a share of 18% of total BERD by the end of the period, while nuclear decreases to about 5%. Conventional technologies-whether coal, oil or gas-fueled-represent each 10% of BERD. Wind, which represented almost 2% until 1990, more than doubled during the nineties, representing 4.5% in 1997.

Finally, technology cost represents a key input for the analysis of technical change in the power generation technologies. Two categories arise from the analysis, one of very high but steeply decreasing costs (Photovoltaic and Fuel-Cells) and one of medium to low and more gently decreasing cost per installed kWe. Wind and Solar Thermal Power Plants are to some extent an exception as they start with intermediate costs but end, in the case of wind with very low cost level. Regarding medium to low cost technologies Figure 2, nuclear displays a strong increase during the eighties, possibly due to the increase in safety requirements, while GTCC clearly presents the lowest costs since 1975. Wind and Solar Thermal Power Plants are to some extent an exception as they start with intermediate costs but end (especially in the case of wind) with really low cost levels.

Figure 2: Technology costs, low cost technologies, in $90/kWe



2. Problems in the Quantification of Two-Factor Learning Curves

The main vehicle of transmission from a specific R&D action to a desirable effect and certainly the first element in the causality chain is the Two Factor Learning Curve (TFLC) giving technology improvements as a function of both experience (learning by doing) and R&D expenditure (learning by research). TFLCs are in the core of the SAPIENT project. Their specification for energy technologies required the quantification of the parameters defining each TFLC, in particular the estimation of the two learning elasticities. Throughout the project, particular attention was given to the estimation of TFLCs so as to ensure that apart from statistical fit they also displayed sufficient robustness for use in a wide variety of models and especially that they performed credibly in view of R&D policy analysis.

The main criteria used in evaluating estimates of elasticities have been: a) Economic sense, i.e. a priori correspondence of the sign and order of magnitude of the estimates with economic and empirical literature, b) goodness of statistical fit especially in terms of statistical significance of the estimated parameters and c) the simulation properties of the equations in anticipation of their use in complex dynamic models over a long time horizon (testing by assuming a 50% shock in R&D expenditures in the year 1998 and running a reduced form model including the TFLC till 2030).

Initially the estimations were carried out using a constant elasticity multiplicative model which was the specification used for the first estimations attempted in the course of the TEEM project. As expected this specification produced rather poor statistical results in the case of many technologies. The main reason for this has been that both cumulative R&D and cumulative capacity installation are almost by definition monotonically increasing time series, creating problems of multicollinearity (inability to distinguish statistically the two effects). The introduction of “knowledge depreciation” has not significantly improved matters having in addition resulted in some cases in perverse sign of the learning by research effect.

Subsequently an alternative specification was tested implying variable learning by research effect (diminishing returns to cumulative knowledge). This specification outlines an intuitively valid representation implying that initially most of the improvements in the cost performance of a technology are obtained through R&D but as the technology starts being adopted increasingly the gains are obtained through learning by doing effects. This approach (called the “Exponential Approach”) had the merit of removing a good deal of the multicollinearity and a consequent improvement in the statistical properties of the estimated elasticities. However tested in reduced form simulation mode, it became apparent that the equations estimated could in some cases under very reasonable assumptions result in reversal of gains (increases in costs after a "shock" increase in R&D expenditure). In order to avoid this analytically very problematic property it was decided to estimate the equations in difference form. The simulation properties appear at first glance "reasonable", however this approach, as often happens with the estimation of difference equations, has resulted in a significant deterioration in statistical properties (increased variance of the estimates).

In a final effort to overcome the aforementioned complexities, the so called "Hydrid Approach" was formulated. This approach combined the variable-elasticity approach and the differences approach. It used estimates from the exponential approach (which had good statistical properties) while for the simulation exercises it used the differences approach. In terms of the aims of the SAPIENT project, this approach produced the most useful results.

3. Implementing Two Factor Learning Curves in Large Scale Models

At the introductory stage of one of its core objectives, SAPIENT undertook an overview of the existing methodologies for modelling energy technology dynamics and examined the model modifications needed for the inclusion of direct or indirect two factor learning curve mechanisms. This process has led to the identification of key problems and issues that were likely to influence the outcomes of SAPIENT exercises involving the large models and has often led to major modifications of the reference cases produced by the models in an effort to homogenise the assumptions across the project, to the extent that this was feasible given the diversity of their coverage and specification.

The key to a better understanding of results from multi-model analysis is the development of a set of reference projections and the systematic comparison of scenario indicators developed within different models. This was particularly important for the SAPIENT baseline scenarios, which have served as the basis for the sensitivity analysis to estimate the various indicators related to the effectiveness of R&D and the expected productivity of R&D expenditure. For the quantification of the baseline scenarios POLES, MESSAGE and MERGE-ETL were used since they are world energy models that include sufficiently high degree of technological detail for the estimation of R&D effectiveness of specific technologies.

According to the reference scenario developed within the SAPIENT project, the main driving forces underlying the analysis are population growth and economic growth while the key final results are energy consumption and energy and carbon intensities. Some of these driving forces are model inputs and some are derived from model outputs, so an attempt was made to analyse in a summary fashion the relationships among these forces. The relationship was given by the so-called Kaya identity (Kaya, 1990; Yamaji et al., 1991). This identity explains total CO2 (or GHG) emissions as the result of multiplying determining factors (the so-called driving forces); namely population, economic growth, energy intensity, carbon intensity and carbon emissions. More precisely, it establishes a relationship between population growth, per-capita value added (i.e., average global world product, GWP, per capita), energy consumption per unit value added, and emissions per unit energy. In the sequel, trajectories for each of the SAPIENT baseline scenarios are presented for each of the four factors in the Kaya identity. In addition, the SAPIENT baseline trajectories are compared to the ranges of scenarios summarized in the SRES database[1] (Morita and Lee, 1998), of greenhouse gas emissions scenarios.

The SAPIENT baselines differ with respect to the analysed time horizon. The POLES scenario covers a time frame up to year 2030, the MERGE-ETL up to 2050 and MESSAGE presents results for the whole

---

[1] This is a database of greenhouse gas emission scenarios, which was developed as part of the process of compiling the IPCC (Intergovernmental Panel on Climate Change) Special Report on Emissions Scenarios (SRES, 2000). Presently, it includes more than 400 scenarios from 171 published literature sources and other scenario evaluation activities (Weyant, 1993 and Manne and Schrattenholzer, 1996, 1997).

century (up to 2100).Table 1 below gives an overview of the main indicators of the SAPIENT baseline scenarios for the year 2030, the last year for which results are available for all three models.

Table 1: Overview of scenario drivers and results

	Estimates for the year 1990 [c]	Sceanrio Projections		
		MERGE-ETL	*MESSAGE*	*POLES*
Population (billion)	5300	8645	8182	8164
Gross World Product (trillion US$1990) [a]	21	56	85	63
Per Capita Income (US$1990)	3940	6533	10407	7773
Primary Energy Use (EJ)	352[b]	712	901	706
Energy Intensity of GWP (MJ/US$1990)	16.8	12.6	10.6	11.1
Carcon Intensity of Energy (kgC/MJ)	17	15.2	14.0	16.9
Carbon Dioxide Emissions (GtC)	5.9	10.8	12.6	11.9

[a] *The scenario's GWP for the year 2000 was standardized to 30.3 1997US$ (EIA, 2001). GWP trajectories were calculated from the GWP growth rates of the respective scenario based on the standardized values for 2000.*
[b] *Calculated with the direct equivalent accounting convention (including use of non-commercial energy)*
[c] *1990 estimates: SRES, 2000.*

Population

Population is one of the fundamental driving forces of future emissions. The global population range for all scenarios in the SRES database is from more than six to about 19 billion people in 2100 with the central or medium estimates in the range of about eleven billion. The long term average population growth rate was about 1% pa during the last two centuries and about 1.3% pa since 1900. Currently the world's population is growing at a rate of about two percent per year. The scenarios however, and other global population projections, envision a slowing population growth in the future. Even the highest population projections require 70 years or more for the next doubling whilst the most recent doubling took approximately 40 years.

Gross World Product

According to the SRES database scenario, the average annual growth rate of GWP per capita between 1990 and 2100 ranges from 0.4% pa to 2.2% pa with a median value of 1.6%. Relative to 1990, GWP per capita in 2030 increases by factors between 1.1 to more than 2.7 for the database scenario, while the SAPIENT baseline scenarios project a GWP per capita increase of 1.8 to 2.5 times. This corresponds to annual growth rates ranging from 2% to 3% per year.

Up to the year 2030, the range for GWP in the SAPIENT baseline scenarios is relatively small compared to the range of SRES database scenarios. After 2030 the global economy in the MESSAGE scenario grows at a relatively high pace, creating a pronounced deviation from the rest SAPIENT scenarios.

Primary-Energy Intensity of GWP

Primary-energy intensity of GWP is a summary statistic describing technological progress in the energy system. In all SAPIENT scenarios, economic growth outpaces the increase in energy consumption, leading to substantial reductions in the ratio of primary energy consumption of GWP. Typically, higher GWP growth rates correspond to faster decline rates of energy intensity because in a situation of faster economic growth, inefficient technologies are retired faster in favour of more efficient ones. Also, the structure of the energy system and patterns of energy services change faster with the same effect on the primary-energy intensity.

Therefore, a meaningful comparison of primary energy intensities across scenarios should depict the relationship between energy intensity and economic development. Economic growth between 1960 and 1990 was associated with a reduction in energy intensity on the global level. At early stages of economic development, energy intensities seem to improve faster since highly inefficient technologies are replaced by more advanced ones. The further energy intensities improve, the harder it becomes, and the longer it takes, to achieve additional efficiency improvements.

Accordingly, the energy intensity rate decreases relatively fast (at a rate of 1.3% per year) in the POLES and MESSAGE scenarios. This corresponds to an average energy intensity of about 11MJ/$ in 2030, compared to 12.6 MJ/$ in the MERGE-ETL baseline scenario in the same year. Still, the projections of energy intensity in the SAPIENT baseline scenarios cluster at a comparatively narrow range in 2030 (11-12MJ/$) when compared to the SRES database scenarios where they range from 6 to 17MJ/$.

Carbon Intensity of Energy

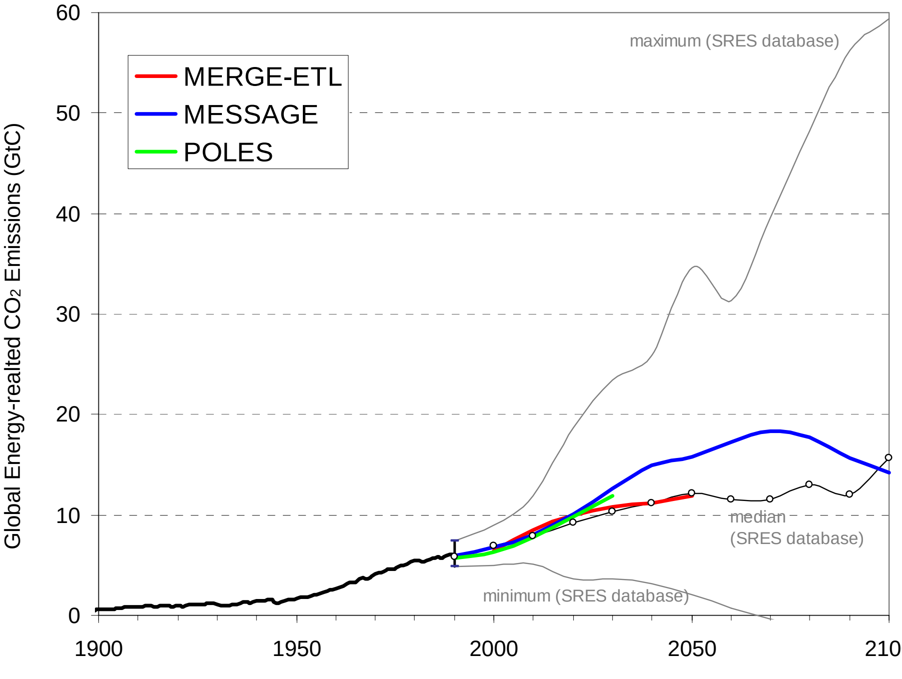
Declining carbon intensity of energy has been termed decarbonisation. The average decarbonisation of the world's energy system has presented a persistent trend of an average 0.3% per year for the last two centuries. The overall tendency towards lower carbon intensities is due to the continuous substitution of fuels with high carbon content such as the coal by fuels with lower carbon content such as natural gas and non-fossil energy sources[2].

In the period 1990-2100, the highest rate of decarbonisation in the SRES database is about 3.3 percent per year whereas the median trajectory corresponds quite closely to the historical rate of decarbonisation with 0.3% per year. The POLES scenario shows the highest carbon intensity across the SAPIENT baseline scenarios, presenting a global carbon intensity of primary energy increase by a factor of 1.1 until 2030. In contrast, the MERGE-ETL and the MESSAGE scenarios include some decarbonisation.

Carbon Dioxide Emissions

The range of CO2 emissions across all scenarios in the SRES database is large indeed, ranging in 2100 from ten times the current emissions all the way to negative net emissions. Many possible factors could interpret this wide range, key among which is the high uncertainty surrounding the development of the main driving forces-population growth, economic development and energy use.

Figure 3: Global carbon dioxide emissions, trajectories in the SAPIENT scenarios and ranges from the SRES database. Also shown is the historical development from 1900 to 1990.



---

[2] However, it should be noted that carbon intensities are increasing in some developing regions. This is especially if emissions from non-commercial energy consumption are not accounted for. In this case, the substitution of non-commercial energy by other (commercial) fossil fuels result in significant emissions increases, which is rather a consequence of the accounting convention than the real change of the countries' carbon intensity.

Figure 3 above shows the global CO2 emissions path for the SAPIENT scenarios, the ranges of the SRES database and the actual emissions from 1900 to 1990. The SAPIENT scenarios use values between 5.7 (POLES) and 5.9 (MESSAGE) GtC of carbon emissions from fossil fuel consumption in 1990, with a trend slightly above the SRES median in the long run.

Global CO2 emissions have increased at an average annual rate of about 1.7 percent since 1900. If this trend continues, global emissions will have doubled by the year 2030. The range of projections by all scenarios is very large around this value of double global emissions. The highest projections by SRES database scenarios have emissions four times the 1990 level by 2030 while the most optimistic scenarios project a level barely above half the current emissions. All SAPIENT baseline scenarios however feature increasing global emissions. Up to the year 2030, the projections are almost identical, clustering in 2030 between 10.8 and 12.6 GtC. This increase corresponds to roughly a doubling of today's emissions. In the longer run (until 2050), emissions increase relatively faster in the MESSAGE scenario, peak at around 20GtC later in the century (in 2060) and subsequently decrease to reach about 14 GtC in 2100.

To sum up, for all analysed scenario indicators, the SAPIENT scenarios show comparatively narrow ranges. Consequently, despite minor differences with respect to some of the driving forces, the SAPIENT baseline scenarios show particularly consistent developments of the resulting carbon emissions. They therefore served particularly well as the basis for the sensitivity analysis to estimate the various indicators related to the effectiveness of R&D.

4. Analysis with large models

As a means of meeting the objective of the endogenisation of technology progress, it was necessary to develop a state of art modelling of technology dynamics in energy models. The point of departure was model modifications for the inclusion of direct or indirect two factor learning curve mechanisms. The estimated TFLCs were subsequently widely tested in the large-scale models under very different conditions. Simulation models had to observe a rigorous application of the TFLC principle and ensure an analytically transparent behaviour. Optimisation models have tested the principle even beyond by obtaining optimal R&D effort allocations under conditions of perfect foresight. Many interesting insights as to the effect of the timing of R&D effort have been gained through these exercises; insights on particular technological options, on the main energy/environment aggregates and notably on CO2 abatement as well as the costs associated with it.

The large-scale models involved within SAPIENT are complementary to each other, either because of their approach, or their regional coverage. As far as the approach is concerned, POLES and PRIMES are market and behaviour-oriented and follow adaptive expectations to simulate the dynamics of the energy system. On the other hand, MARKAL, MERGE and ERIS are bottom-up optimisation models operating under perfect foresight. PRIMES and MARKAL cover Europe, while POLES, MERGE and ERIS are regionalised world models. Model versions enhanced by incorporating an induced technology process mechanism are used throughout the SAPIENT project.

POLES has been developed in an hierarchical structured framework 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 adjustment to prices and a feedback loop through international energy prices. The model is fully operational and can produce detailed long term (2030) world energy and CO2 emission outlooks with demand, supply and price projections by main region. POLES follow a portfolio analysis approach to the R&D decision process. Exogenous public policies provide both the environmental constraint (either in the form of quantitative targets or of GHG emission penalty) and the impulse or "technology push" through public R&D spending. Cumulated R&D is incorporated as an explanatory variable for technological progress representing the "learning by doing" part, while cumulative capacities account for the "learning by searching" part. The module captures both the supply and demand sides of energy technology market. 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.

The perfect-foresight cost-optimisation models ERIS, MARKAL and MERGE develop new scenario results covering the post-Kyoto time horizon up to 2050. The multi-regional version of the ERIS model prototype examines electricity generation technologies in a global context, capturing the main mechanisms of endogenous analysis of technological learning under uncertainty, allowing for a consistent cost-benefit analysis of specific policies aiming at technology optimisation. Impacts of Kyoto-like CO2 constraints are analysed considering the effects of allowing or not emissions trading. Complementary stochastic analyses addressing the uncertainty of emission constraints, demand and learning rates are presented. In parallel, several sensitivity analysis runs of ERIS explore the impact from varying learning rates and the role of different depreciation knowledge stock rates on R&D effectiveness. The analysis considers non-linear programming (NLP), however solving the NLP version with conventional solvers enabled the identification of only the locally optimal solution. Alternatively, the solution of the linearised Mixed Integer Programming (MIP) approximation to the single-factor formulation of the learning curve was applied as a starting point for the two-factor NLP problem. The latter procedure has been shown to provide a better local optimum in previous experiments. However, the two-factor NLP solution has not been identified as capable of providing the global optimum.

The MERGE model is a well-established tool for assessing economic and technological options to deal with the global climate change issue. In MERGE the world is divided into nine geopolitical regions. An ETA-MACRO model describes each of these regions. ETA is a “bottom-up” engineering model which captures substitutions of energy forms and energy technologies to comply with CO2 reduction targets, while MACRO is a “top-down” macro-economic model which captures macroeconomic feedbacks between the energy system and the rest of the economy, for instance impacts of higher energy prices (due to CO2 control) on economic activities. The mathematical formulation of ETA-MACRO can be cast as a convex non-linear optimisation problem, where the economic equilibrium is determined by a single optimisation. MERGE aggregates the regional welfare functions into a global welfare function; the problem solution corresponds to a Pareto optimal equilibrium which maximises this global welfare function.

Finally, much experience was gained from experiments with the comprehensive energy system model MARKAL for Western Europe, augmented to include endogenous technology learning based on the learning-by-doing mechanism. These experiments have confirmed the benefits expected from the adoption of the mechanism. The work with MARKAL takes into account the interdependency between clusters of technologies, rather than considering individually learning technologies. Some Monte Carlo uncertainty analysis methods have been applied to a complex energy system model like MARKAL. Despite computational complexity and rather higher solution times, the model proved able to perform MC analysis in combination with scenario analysis, including endogenous technology learning.

4.1. POLES experiments

The usual and simplest approach to model technology improvement in energy models is by introducing exogenous forecasts on technology development. This type of exercise has been performed at the beginning of the project with the updated databases and scenario hypotheses in the SAPEX (Sapient exogenous) scenario. This preliminary scenario has then been used as a benchmark for the assessment of the SAPEN (Sapient endogenous) scenario. In the latter case exogenous hypotheses have been replaced by a description of technology cost dynamics which endogenises, at least partially, technological change in the new and renewable technologies and in the electricity modules of the POLES model.

4.1.1. The SAPEX scenario to 2030

The SAPEX scenario provides an image of how the world energy system may develop in the next decades in a “business and technical change as usual” context and with exogenous technology performance and costs. According to this scenario, world population and economy will remain key driving forces in the development of the energy sector over the next decades. In specific, world population growth rate will continue to decrease from 1.5% per year in the past decade to 1% per year over the 2000 to 2030 period. This results in a total population of 8.2 billions in 2030, from 6.1 billions in 2000.

World economic growth will be slightly above 3%/year for the next thirty years, while the world average per capita GDP growth will markedly accelerate in the 2000-2010 decade, mainly due to the projected economic recovery in the CEEC (Central and Eastern European Countries) and CIS region.

The combination of the continuous slowdown in the population growth and per capita GDP rates results, after the initial upsurge, to an economic growth rate that is weakening over time, from 3.5 %/year in the first decade, to 3.1 %/year in the following decade and finally 2.6 %/year between 2020 and 2030.

Turning to per capita GDP levels, the projections show some convergence across the different world regions. After the 1990-2000 decade during which Western Europe and the Japan and Pacific regions lost some ground comparatively to North America, some catch-up of the former regions occurs in the following decades. In the economies in transition, the per capita GDP ratio relative to North America follows a much more uneven trajectory, with a huge drop from 1990 to 2010. A sustained recovery follows, without however allowing a full recovery of the 1990 ratio at the end of the projection. In the developing regions, the growth rates appear more contrasted. Asia sees a significant improvement, Latin America follows a much more limited convergence process while the Africa and Middle-East regions do not experience any convergence.

Technology diffusion and improvement in the SAPEX case, using the Learning curve approach as a filter that is applied ex-post to the model's result, show trajectories that are consistent with a regular learning-by-doing effect for some technologies, but not for all of them.

The oil-price path obtained from the model only indicates a trend that is consistent with the relative dynamics of world supply and demand and does not pretend to provide a precise oil-price forecast. Gas price ranges from 28€/boe in the Euro-African market, to 33€/boe in American and European markets in 2030. Coal price however is independent of oil price and is projected to reach levels of about 10€/ton in 2030.

World energy consumption is projected to increase by some 70% between now and the year 2030, mainly reflecting different population and economic growth dynamics, higher energy prices and more efficient technologies.

In 2030, fossil fuels represent almost 90% of world energy consumption. Oil remains the main source (34%) of energy, while coal is the second biggest source of supply (31%). Natural gas, despite its very rapid growth in the power generation sector, represents only one fourth of the world energy supply by 2030. Nuclear energy increases only slightly in absolute terms over the projection period (5% in 2030). As far as renewable sources are concerned, the share of hydropower and geothermal stabilises at 2%, while wind, solar and small hydro contrary to their marked diffusion acceleration represent in 2030 less than 1% of gross inland consumption.

Globally, energy from renewable sources is projected to cover 8% of world energy requirements in 2030. This is less than the 13% share observed in 2000 and is essentially due to the continuous decline of traditional biomass consumption in Asia and Africa, due to increased urbanisation, deforestation and substitution to modern energy forms in rural areas. These changes in the primary fuel-mix have a considerable impact on the carbon intensity of the world energy system and on the associated CO2 emissions.

World CO2 emissions more than double over the 1990-2030 period with China being the largest world CO2 emitter (in absolute terms) towards the end. Nuclear energy world market share goes down to 10% of total electricity production in 2030, from 18% in 2000. Finally, despite the remarkable growth of electricity production from renewable technologies (more than 4% pa on average), electricity from renewable resources is not expected to exceed 3% of world total production in 2030.

4.1.2. Endogenisation of Technical Change: the SAPEN case.

Learning curves taking into account both "learning by doing" and "learning by research" effects are the key elements for the endogenisation of technical change in the POLES model and for the introduction of a causality link between R&D variables and technology performances. The TFLCs provide the dynamics for technology improvement depending on the cumulative capacities for the “learning by doing” part and on the cumulative knowledge stock (R&D) for the “leaning by searching” part.

With harmonised hypotheses on the learning parameters, the SAPEN case yields projections of technology development that are more consistent, both with historic trends and in an inter-technology comparison perspective, than in SAPEX case. A comparison of the SAPEX and SAPEN case results, when using the “ex-post learning curves” as ways of characterising the technology improvement dynamics, indicates that the behaviour of the model is more satisfactory and the results more consistent in the endogenous technology case than in the exogenous one.

The new trends in technology development, as simulated in the SAPEN case, lead to significant changes in the structure of electricity production. Clean coal technologies and electricity from waste benefit of significantly increased capacities in the endogenous technology SAPEN case compared to the SAPEX case. Moreover, other new and renewable technologies also show capacity increases in relative terms whereas conventional technologies (oil, lignite, coal) show reduced capacities. Consequently, the investment cost of advanced coal technologies and of renewable technologies is lower in the SAPEN (by about 30% and of 20%-50% respectively) whereas most conventional technologies show higher investment costs.

4.2. The impact of carbon constraints on Technical Change

The SAPIENT carbon constrained reference case (SREF) has been developed to simulate and assess the impact of global constraints at world level and for the 2030 horizon. It describes a reasonable hypothesis for the development of CO2 emissions, taking into account the different regions’ willingness to commit themselves in medium-term reductions as well as the expected reinforcement of climate change policies beyond the year 2010. The SREF case is designed through the introduction of a penalty for CO2 emissions within the POLES model and follows an emission path consistent with an objective of stabilisation of greenhouse gas concentration around 500 to 550 ppmv (twice the pre-industrial concentration) by the end of this century and a global temperature rise of no more than 2°C relative to the year 1850. In order to take into account the commitments of the industrialised countries for the Kyoto period, the carbon penalty is differentiated by main regions up to 2010, but remains stable across all regions until 2030 in order to meet an emission path that is compatible with the concentration target.

The carbon penalty introduced in the SREF case leads to a 21% decrease in CO2 emissions, compared to the SAPEN case. Nevertheless, world CO2 emissions in 2030 still increase compared to their 1990 level. Apparently, the carbon penalty in SREF allows a slowdown in the growth of CO2 emissions but does not trigger a strong trend towards the progressive “decarbonisation” of the world economy.

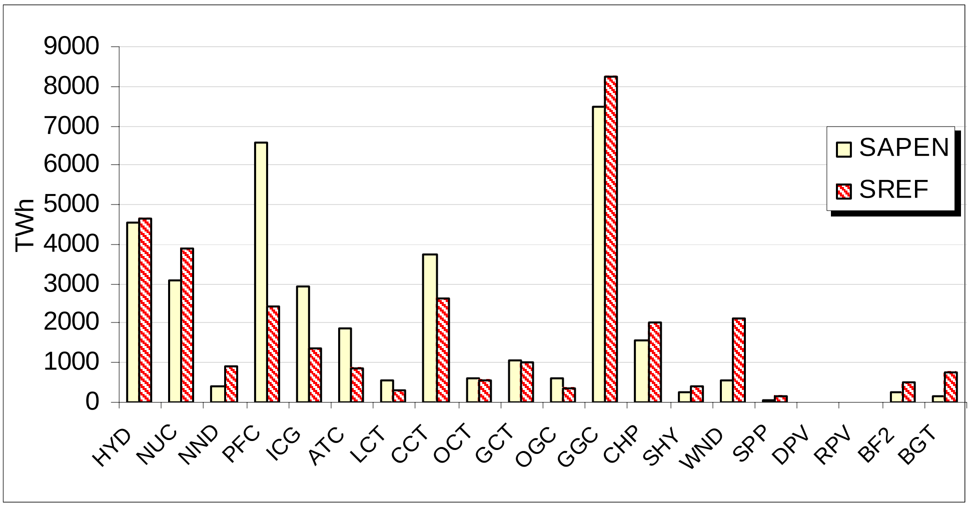
A key outcome of the SREF case is that about half of the reduction comes from the decrease in total energy demand while the other half comes from changes in the world primary energy-mix.

The SREF case projects a 10% reduction in the carbon intensity of the world total consumption, which in turn reflects the opportunities for fuel substitution in the energy system. Figure 3 illustrates the changes in the technology mix for electricity generation. As expected, the carbon penalty affects primarily the fuels with the highest carbon content, namely coal (-43 %) and oil (-8%), leaving natural gas unaffected, as the impact of reduced global demand is compensated by significant substitutions from gas to coal. The market shares lost by coal and oil are balanced by substantial increases in nuclear and renewable energies[3] compared to the SAPEN case. Within the renewable sources wind, solar, small hydro and biomass gasification experience the greatest increase in relative terms.

---

[3] Biomass, wind, solar, small hydro, large hydro, geothermal and wastes.

Figure 4: Technology mix in world electricity generation in 2030.



4.3. ERIS Experiments

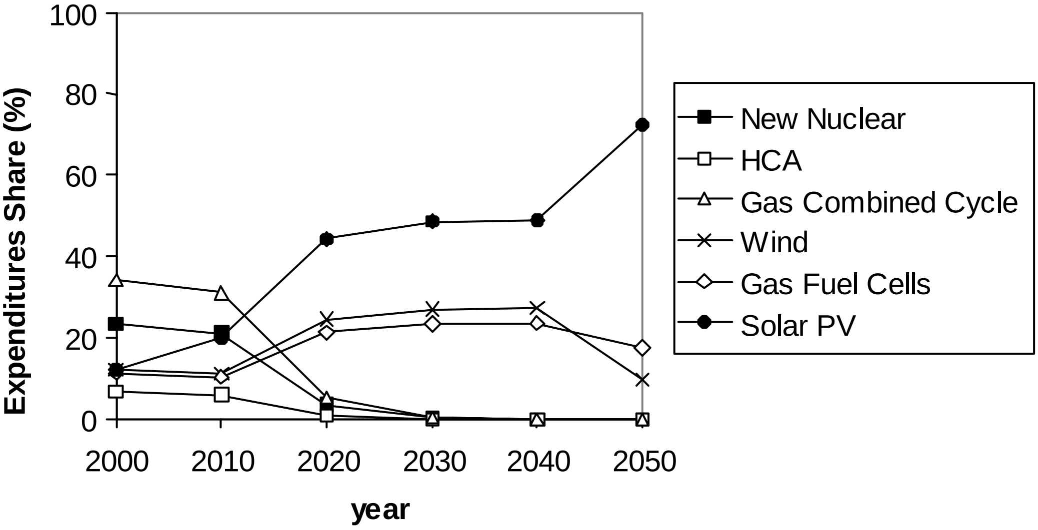
The 2FLC formulation applied in ERIS allows endogenising two basic learning channels, namely the accumulation of capacity and R&D expenditures within a perfect-foresight framework. The two-factor learning curve scheme implemented in ERIS, allows the consideration of the effects of cumulative R&D expenditures together with those of cumulative capacity on cost reductions of technologies. When R&D expenditure per technology, introduced in ERIS, is kept exogenous it allows the examination of the effects of assigning a given amount of R&D resources to a given technology, and can help determine the amount of R&D money that is necessary for a technology to become competitive under certain circumstances. In the endogenous specification of R&D expenditures a global R&D budget is provided and the model finds its optimal allocation among the different learning technologies taking into account a number of intervening factors.

In order to reflect the fact that time lags and depreciation occur in the R&D process, a knowledge stock function is introduced in place of cumulative R&D expenditures. The knowledge stock formulation allows considering the delay between R&D spending and productivity gains (in this case cost reductions) and takes into account the possibility that past R&D investments depreciate and become obsolete. Through the depreciation rate an element of "forgetting-by-not-doing" is introduced where if no efforts on R&D are made on a given technology, its investment costs will increase. ERIS also examines the dependence of optimised R&D expenditures for a given technology on its own learning-by-doing and learning-by-searching elasticities and on those of a competing technology.

The analysis of Kyoto-for-ever scenarios indicates that a significant departure from carbon intensive generation options is required to fulfil the CO2 emission targets. The generation mix appears to be dominated by less carbon intensive technologies. With an endogenous representation of technology dynamics, early up-front R&D expenditures are made, with a strong declining trend in the following periods. Thus, the results indicate that R&D spending is effective only once sizeable spending in cumulative capacity takes place. In reality, however, R&D expenditures are in many cases a precursor of the accumulation of experience through capacity deployment. Specifically, they can be essential in the first stages of development of the technology, before it goes to the marketplace. This drives to the more general question of the role of the two learning channels in different stages of the life of a given technology.

In terms of absolute values of R&D expenditures in each learning technology, solar photovoltaic, namely the technology with the highest learning by doing and learning by searching rates, dominates the allocation of R&D resources. Figure 5 below shows the relative share of each technology on the fraction of the R&D budget actually spent. The results clearly indicate that the gas fuel cell and the wind turbine also receive significant fractions of the R&D funds. However, R&D investments in the gas combined cycle turbine, clean coal technology, and the nuclear plant technologies decline and disappear, despite being the technologies which received the highest amount of resources in the first period. Apparently, technologies with higher LSRs appear to be more attractive for expending R&D resources. However, other factors such as the LDR, the maximum growth rates allowed and the presence or absence of a constraint on emissions, which may force low-carbon technologies into the solution, play also an important role.

Figure 5: Share of the total annual R&D expenditures allocated to each learning technology.



Some of the robust results indicate that the optimised R&D levels are sensitive to both learning parameters, but in different directions. Higher LDRs correspond to lower levels of optimised R&D support, but higher LSRs correspond to the higher levels of optimised R&D spending. However, if sufficient capacity cannot be installed, no R&D spending occurs, implying that a technology must promise to pay back the investment made in it. Finally, competition in terms of R&D support and market shares between technologies, turns out to be of secondary importance, and no "lock-in" or "crowding-out" phenomena were observed.

4.4. MERGE-ETL Experiments

The inclusion of endogenous technological learning in MERGE involved the utilisation of distinct one-factor (learning by doing-1F) and two-factor (learning by doing and by searching-2F) learning curve formulations. Due to the increasing returns associated with technological learning, the endogenisation of technological learning in MERGE yields a non-linear non-convex optimisation problem. Because of this non-convexity, the traditional tools used to solve MERGE do not guarantee to find the global optimum of MERGE-ETL, but only a local. In order to find the global optimum, a heuristic iterative approach in three steps was employed.

To study the impacts of modelling endogenous technological change in MERGE-ETL, several scenarios have been considered related to CO2 emissions (carbon control case) and technological learning. Allowing for endogenous technological progress yields a decrease of energy production costs over-time, as knowledge in the different technologies builds up. In other words, the production factor energy becomes less expensive overtime. It can thus substitute partly for the two other production factors capital and labour. Consequently, primary energy use is lower in the 2F case compared to 1F case, whereas the opposite takes place in the carbon control case. This is due to opposite variations in overall GDP. Furthermore, the reduction of primary energy use due to carbon control is lower when considering endogenous technological change. The primary energy mix also alters; the share of fossil fuels decreases while the shares of nuclear and renewable energy (mainly wind and biomass) increase. These trends are even stronger when considering knowledge accumulated through R&D spending (2F case).

Electricity generation is always higher in the 2F as compared to the 1F cases. The reduction of electricity generation due to carbon control is lower when considering endogenous technological change. Indeed, technological generation costs decrease overtime for learning technologies, and electricity can thus partly substitute for capital and labour as production factors. In addition, the numerical application shows that technological learning favours new advanced systems such as gas turbines with combined cycle, advanced nuclear plants and wind turbines. Moreover, the analysis projects economic benefits of endogenous technological progress through the lowering of the marginal abatement costs, which in turn reduces GDP losses for CO2 emissions reduction. Essentially, the learning mechanism renders the production of energy cheaper. Allowing for carbon controls, world GDP is projected at slightly higher levels in the 2F case compared to 1F. This means that the exogenously determined R&D spending on energy technologies is not efficient in the TFLC case, where it would be better to improve the productivity of the other two production factors (capital and labour). However, with the necessity to curb carbon emissions, R&D spending on energy technologies becomes economically efficient in the TFLC case. Clearly, technological progress plays a fundamental role in the evolution of energy systems as it favours the transition towards more efficient and cleaner energy technologies.

5. The ISPA meta-model for R&D budget exploration

Central to the SAPIENT approach is the elaboration of a small aggregated model named ISPA (Integrating System for Priority Assessment), specifically designed for R&D budgeting policy exploration. In essence, the ISPA model explores 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. In recognition of the nature of such policy, namely that it pursues a number of aims and that R&D is essentially a speculative activity, ISPA takes the form of a multiple objective stochastic non-linear optimisation problem where the probability that an objective exceeds a given desirable threshold is maximized subject to the condition that the probability that the other objectives exceed given thresholds is greater than a certain level. Naturally the budget allocations must also be kept non-negative. A concrete specification of this problem has been coded and tested here in view of gaining insights for a method of policy option explorations.

The key features of ISPA are:

- A single horizon i.e. the budget allocation is assumed to be decided at some time near the present aiming to obtain some desired effects on a fixed future horizon (an essential feature of this type of exercise where it is clearly understood that allocations in future dates can be postponed and can incorporate knowledge acquired in the meantime).
- In recognition of the essentially speculative character of R&D budgeting ISPA treats the impact of allocation decisions stochastically giving the possibility to make probabilistic statements.
- Statistical dependence of impacts arising from the fact that they are often affected (albeit differently) by the same variables that are themselves subject to risk.
- The allocation itself does not affect the stochastic characteristics of the problem. This is clearly a simplifying assumption, which however is necessary in order to keep the model specification manageable. It can be justified in terms of the relatively limited significance of the budget allocation compared to the sources of risk. Under certain conditions it can be envisaged to allow average impacts (as opposed to their risk characteristics) to depend on budget decisions, the main consideration being the maintenance of a convex set in order to avoid the presence of local optima.

ISPA provides the main mechanism through which R&D action translates into results in terms of specific objectives. These objectives are oriented towards certain policy issues key among which are energy demand and supply, the state of the environment and the economy. It was envisaged early in the project that the following set of objectives should be integrated in the meta-model.

- The market return on R&D investment as a measure of technology profitability.
- Environmental impacts and most particularly the effects on energy related greenhouse gas and CO_2 emissions leading to global warming.
- The total energy costs for the consumers (firms and households).
- Global societal targets such as the security of supply.

Emphasis was also placed in the quantification of the parameters used for the performance of the definitive policy exploration exercises. These parameters were of two types:

- Reaction functions linking the expected impact of an R&D action on the objectives of the R&D policy as retained.
- Stochastic information (basically variances and co-variances) on these impacts.

The latter type of parameter estimation presented formidable challenges of a theoretical and practical nature as no such work seemed to have ever been undertaken and methodologies had to be established and tools developed from scratch. It was therefore decided to construct a dedicated tool covering the whole range of information required and capable of incorporating results from diverse sources (expert panel consensus opinion, statistical analysis and indirect use of the large models as means of obtaining the stochastic characteristics of the reactions necessary for building ISPA). This tool which was originally envisaged to have an auxiliary role ended as an original large scale stochastic model of the energy system.

6. The PROMETHEUS World Stochastic Energy Model

The required purpose built tool was named PROMETHEUS and took the form of a self-contained energy model consisting of a set of stochastic equations. PROMETHEUS is a compact partial equilibrium model, containing a set of relations and variables for all the main quantities which are of interest in the SAPIENT project. These include demographic and economic activity indicators, energy consumption by main fuel, fuel resources and prices, CO2 emissions, technology uptake and two factor learning curves. All exogenous variables, parameters and error terms in the model are stochastic with explicit representation of their distribution including in many cases terms of covariance. It follows that all endogenous variables as a result are also stochastic.

By necessity, PROMETHEUS is an aggregate model especially in terms of regional coverage. However this isn’t a particular handicap as:

- There are diminishing returns to detail in terms of error reduction.
- The ISPA meta-model, where PROMETHEUS results are used, adequately incorporates error and can be run giving useful insights even with relatively large ones as long as they are balanced across choices.

The main output of PROMETHEUS is a large data set of Monte-Carlo simulations involving all the variables of the model, key among which are the technology-by-technology R&D impacts on the objectives which after some processing were directly usable in the ISPA integrated policy analysis tool. PROMETHEUS was early identified as an extremely useful tool with considerable scope for applications in the Energy, Technology and Environment domain adding.

The output of the Monte Carlo data set is used to fit joint Normal or Lognormal distributions for the impact variables to be used in the ISPA model. Apart from that, the PROMETHEUS output data set can be used in its own right, as strategically or analytically important information on risks and probabilities regarding the variables incorporated in it or any pre-determined function involving them. Some major applications include security of supply assessment, environmental risk assessment or investment risk analysis. Indicative examples are the probability that CO2 emissions exceed a certain level, the probability distribution of oil prices, or the risk that a particular technology may be uncompetitive vis-à-vis another technology for a given load.

PROMETHEUS relies heavily on econometric estimation to provide the essential stochastic information. One of the main advantages of this reliance is that such estimations provide an element of objectivity. Moreover, the reliance is amenable to the analysis of co-variance both in terms of statistical dependence of the parameters and in terms of the simultaneous solution of sets of econometrically estimated equations. It also tends to force the analyst to investigate the nature and extent of stochastic elements (why past variability occurred).

On the negative side however, this implies an excessive reliance on the evidence from history. However it is not clear whether this reliance leads to exaggeration or under-estimation of variability – therefore the method does not in itself produce systematic bias.

The model has been specified to cover three regions: OECD Europe, Other OECD (USA, Canada, Japan, Australia, N. Zealand), Rest of the World and a number of final demand categories: a) Industry (non-electric uses), b) Transport, c) Residential/Commercial/Other (non-electric uses), d) Industry (electric uses), d) Residential/Commercial/Other (electric uses). As Fuels/Energy forms for final demand it identifies, Coal, Oil, Natural Gas, Electricity and consumer prices for Coal (Industry), Oil (Heavy and Light Fuel Oil, Gasol54ine), Natural Gas (Industry, Residential) and Electricity (Industry, Residential).

Special attention was given to the power generating sector which constitutes an area of particular attention in the SAPIENT project: PROMETHEUS covers Generation from “existing” Fuels/Sources (Coal, N. Gas, Oil, Nuclear, Hydro) and makes provisions for Generation by “new” Source/Technology (Renewables, Advanced gas, New Nuclear, Fuel Cells), identifies capacity by “existing” and “new” technologies, incorporates Capital Costs by Technology Type and naturally covers R&D expenditure by technology considered in the SAPIENT project.

6.1. PROMETHEUS General Results

Having estimated and constructed PROMETHEUS, the model was run for one thousand times and results were obtained. The results data set is of considerable interest with a large potential for analytical applications.

The table below provides some summary statistics for a small selection of key variables at World level for the year 2030.

Table 2: Summary statistics for a small selection of key variables at World level for the year 2030.

KEY PROMETHEUS VARIABLES(WORLD 2030)	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Prob. Test for Normality	Prob. Test for Log Normality
Population th.	8112245.0	8114811.0	8359936.0	7765037.0	95308.7	-0.01	2.76	0.29	0.28
GDP million 95$	88538878.0	88400186.0	121000000.0	65340228.0	7365036.0	0.18	3.15	0.04	0.56
GDP per capita th. 95$	10.9	10.9	14.6	8.2	0.9	0.17	3.09	0.08	0.58
CO2 Emissions mil. tonnes	45650.5	44916.5	77663.8	26005.6	7603.9	0.58	3.56	0.00	0.59
Effective Carbon Value $95/t.Co2	34.6	30.3	211.7	0.0	20.7	1.71	9.56	0.00	0.13
Yet to be discovered conv. oil (Bil. Bl)	960.81	898.82	3243.57	248.20	369.96	1.30	6.36	0.00	0.69
Yet to be discovered gas (Trillion m3)	172.23	150.51	1044.61	30.56	100.43	2.62	15.66	0.00	0.00
World Oil price $95/bl	37.2	35.1	133.5	9.3	13.8	1.74	9.46	0.00	0.00
Gas Price $95/toe	223.7	209.5	679.7	61.9	88.1	1.08	4.84	0.00	0.14
Coal Price $95/tce	32.2	29.4	132.0	7.5	13.6	1.78	9.48	0.00	0.01
Middle East oil prod. Th.bl	29702078.0	29029130.0	53589551.0	9541125.0	5476927.0	0.82	4.64	0.00	0.00
Non-Conventional oil prod. Th.bl	4385976.0	3964064.0	13002069.0	322841.9	2434419.0	0.79	3.21	0.00	0.00
Non-Middle East Conv. oil prod. Th.bl	13451766.0	12713661.0	40240184.0	4830011.0	4435692.0	1.10	5.61	0.00	0.79
World oil prod. Th.bl	47539820.0	46702017.0	77454204.0	28651117.0	7542013.0	0.78	3.86	0.00	0.00
Oil Demand MTOE	6468.0	6354.0	10538.0	3898.1	1026.1	0.78	3.86	0.00	0.00
Nat. Gas Demand MTOE	3855.7	3794.9	5992.6	2283.6	570.0	0.62	3.48	0.00	0.06
Coal Demand MTOE	4261.2	4082.8	9479.0	1575.2	1339.1	0.80	3.81	0.00	0.43
Electricity Prod. TWH	37124.3	36628.0	58143.3	22859.0	5457.6	0.56	3.45	0.00	0.30
Final Cons. of Elec. Industry MTOE	1065.6	1045.0	2043.1	546.2	208.2	0.78	4.24	0.00	0.13
Final Cons. of Elec. Resid/Com MTOE	1445.9	1411.4	2780.5	847.1	261.6	0.73	3.82	0.00	0.02
Oil fired Power Prod. TWH	1286.3	1192.3	5202.1	481.4	465.7	2.10	12.40	0.00	0.00
Gas fired Power Prod. TWH	10107.0	9758.1	21241.1	4739.4	2545.6	0.73	3.76	0.00	0.60
Coal fired Power Prod. TWH	12512.5	12066.1	31200.1	3940.6	4166.3	0.76	4.04	0.00	0.01
Nuclear Power Prod. TWH	4017.1	3740.1	13344.2	2793.2	991.2	2.76	17.07	0.00	0.00
Large Hydro Power Prod. TWH	4954.7	4956.5	5575.6	4360.6	202.0	0.02	2.94	0.89	0.40
Power Prod. From NREN sources TWH	4246.8	3125.5	19270.3	101.4	3466.5	1.28	4.45	0.00	0.00

A cursory look at this table indicates that some variables like population, Large Hydro production but also GDP display relatively low variability. The broad energy aggregates such as demand for the main fuels and electricity as well as CO2 emissions display somewhat higher variability though of a similar relative order among them with the exception of coal which due to the uncertainties surrounding eventual measures to tackle the Climate Change issue, is characterized by higher variability. Primary fuel prices are apparently much more volatile in line with considerable uncertainties surrounding undiscovered resources of fossil fuels. Finally very high variability is displayed by non-conventional oil production (due mainly to variability in world oil prices), the effective carbon value and the contribution of new and renewable power generating options (due to an accumulation of uncertainties surrounding the two factor learning curves and hence their cost performance as well as carbon abatement policy in the context of an otherwise quite volatile energy environment).

With the exception of Hydro production and World population the probability that the Monte-Carlo samples come from normal distributions is negligible. On the other hand a much larger number of variables could be said to be possibly Log-Normally distributed. In fact when passing to the logarithms of variables skewness is reduced in almost all cases.

Turning to the correlation matrices between the key variables for 2030, the analysis indicates a predominance of positive correlations even between prices and the corresponding consumption categories. This indicates a relative dominance of supply constraints in price formation. Important strategy implications arise from such a state of matters: variability in the future seems to extend predominantly along an axis ranging from low to high activity, energy consumption, GHG emissions and prices.

6.2. Implementation of Target Variables

As shown previously, the final set of policy objectives under scrutiny at the ISPA stage have been integrated in PROMETHEUS and key results have been delivered. The following section concentrates on the methodology and the measurement of impacts of injecting R&D expenditure shocks on some key energy technologies with respect to the policy objectives specified in the course of the ISPA modelling.

The following general formula was used for the measurement of the impacts:

Impact on ith objective = (Change in ith objective measured in specific units)/ (Change in R&D expenditure in euro)

The above formula illustrates that the change in one objective is a model result arising from introducing a once-off positive shock on R&D allocated to the ith technology at the beginning of the forecast period. R&D shocks applied were equivalent to ten percent of cumulative R&D expenditure for the particular technology however in some cases alternative sizes were used when it was found they gave rise to more meaningful impacts. Shocks were orthogonal applied at the beginning of the forecast period (affecting one technology at the time). In some cases some combined shocks were applied (a uniform expansion of cumulative R&D on all technologies) to enable an eventual extension of the expected productivity of R&D functions to include interdependence. The sections below deal with the different objectives in turn.

i. The market impact objective - ‘profitability’

The market impact was finally represented by a composite index of two desirable incomes namely a technological cost reduction and the increase in volume sales. Given the above, the final indicator was:

Impact = discounted ((reference cost -R&D induced cost)*change in equipment sales volume)/R&D expenditure shock

The above scheme enjoys some clear advantages in the sense that it overcomes some problems encountered with previous versions, introduces some notion of appropriation, hitherto completely absent from the calculations and gives better relative measures for productivity of R&D expenditure on different technologies. The latter point is crucial because in policy analysis, relative impacts entail higher explanatory value.

ii. The CO_2 limitation objective

To ensure transparency, comparability of results as well as facility of implementation the measure of the impact of R&D action on cumulative emissions was retained for the CO2 limitation objective. The CO2 - problem being global the variable of interest was cumulative world emissions. In this way, the formula for impact was defined as:

Impact = change in cumulative emissions/ R&D expenditure shock

Expected impacts with respect to this objective can normally be either positive or negative. PROMETHEUS results suggest that for many technologies (notably the clean coal ones but also gas fired ones) the range of the distribution includes zero with non-negligible probability densities. It was therefore important to express impacts also in terms of relative reductions in cumulative CO2 emissions in order to retain the possibility to use as an alternative the Log Normal distribution in the ISPA policy tool.

iii. The consumer cost reductions impact

This objective has been retained separately for the EU and for the developing World. The calculation was given by the following formula:

Impact = (R&D induced total discounted cost to the consumer - reference total discounted cost to the consumer)/R&D expenditure shock

All final energy consumers (households and firms) were considered in the calculation. Expected impacts with respect to this objective were normally negative. However, PROMETHEUS results suggest that for some rather “exotic” technologies (notably photovoltaic technologies) the range of the distribution includes zero again with non-negligible probability densities. The same applied albeit to a lesser extent at the tails of distributions for some fossil fuel technologies where their enhanced adoption arising from R&D actions combined with particularly severe resource limitations produce small increases in overall cost due to higher fossil fuel prices affecting all consumers. It was therefore important to express impacts also in terms of relative reductions in total discounted cost to the consumer in order to retain the possibility to use as an alternative the Log Normal distribution in the ISPA policy tool.

iv. The impact on security of supply

This objective was defined as follows:

Impact = (maximum increase in oil and gas prices in any 3 year period of the horizon after the shock has been introduced - maximum increase in oil and gas prices in any 3 year period of the horizon in the reference)/ R&D expenditure shock

PROMETHEUS incorporates a Middle East productive capacity constraint subject to fluctuations equivalent to those experienced in history as an element in price formation and is therefore capable of producing sufficiently meaningful outcomes. This objective was found to display high differentiation from the other objectives (for example, R&D expenditure on some technologies like clean coal and nuclear was found to be very productive in contrast to their performance in terms of other objectives) and was therefore found to be susceptible of introducing interesting elements in the R&D strategy analysis to the extent that different priorities are attached to it.

Table 3: Key statistics for the PROMETHEUS objectives.

	PROFITABILITY		CUM. CO2 CHANGE		SECURITY OF SUPPLY		CHANGE IN EN. COST	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Advanced Thermodynamic Cycle (coal)	0.08	0.07	0.04	0.02	-1.71	2.04	-0.22	0.12
Biomass Gasification Gas Turbine	10.29	12.03	-0.67	0.88	-8.78	20.31	-2.28	3.16
CHP with Combined Cycle	0.69	0.82	0.05	0.06	3.19	6.62	-0.51	0.6
Decentralised Photovoltaic cells	3.18	3.98	-0.09	0.09	-0.47	0.97	0.53	0.9
Gas Turbine in Combined Cycle	10.56	6.54	-0.44	0.25	6.46	18.2	-2.86	1.55
Integrated Coal Gasification	3.88	2.85	0.18	0.1	-8.34	9.11	-1.3	0.57
Advanced Lignite	0.2	0.22	0.07	0.04	-0.85	0.96	-0.73	0.4
Fuel Cell Power Generation	3.15	4.94	-0.04	0.13	2.28	7.4	-0.07	0.5
New Evolutionary Nuclear Design	0.02	0.02	-0.01	0.01	-0.17	0.27	-0.04	0.04
Oil Fired Gas Turbine	0.87	0.97	0.22	0.17	20.71	37.88	2.29	1.76
Super Critical Coal	3.07	2.06	0.42	0.2	-16.12	15.31	-2.16	0.96
Solar Thermal Power	6.83	10.84	-0.13	0.23	-1.17	3.12	-0.03	0.2
Wind Turbines	22.29	16.92	-0.85	0.76	-6.26	9.91	-2.2	3.8

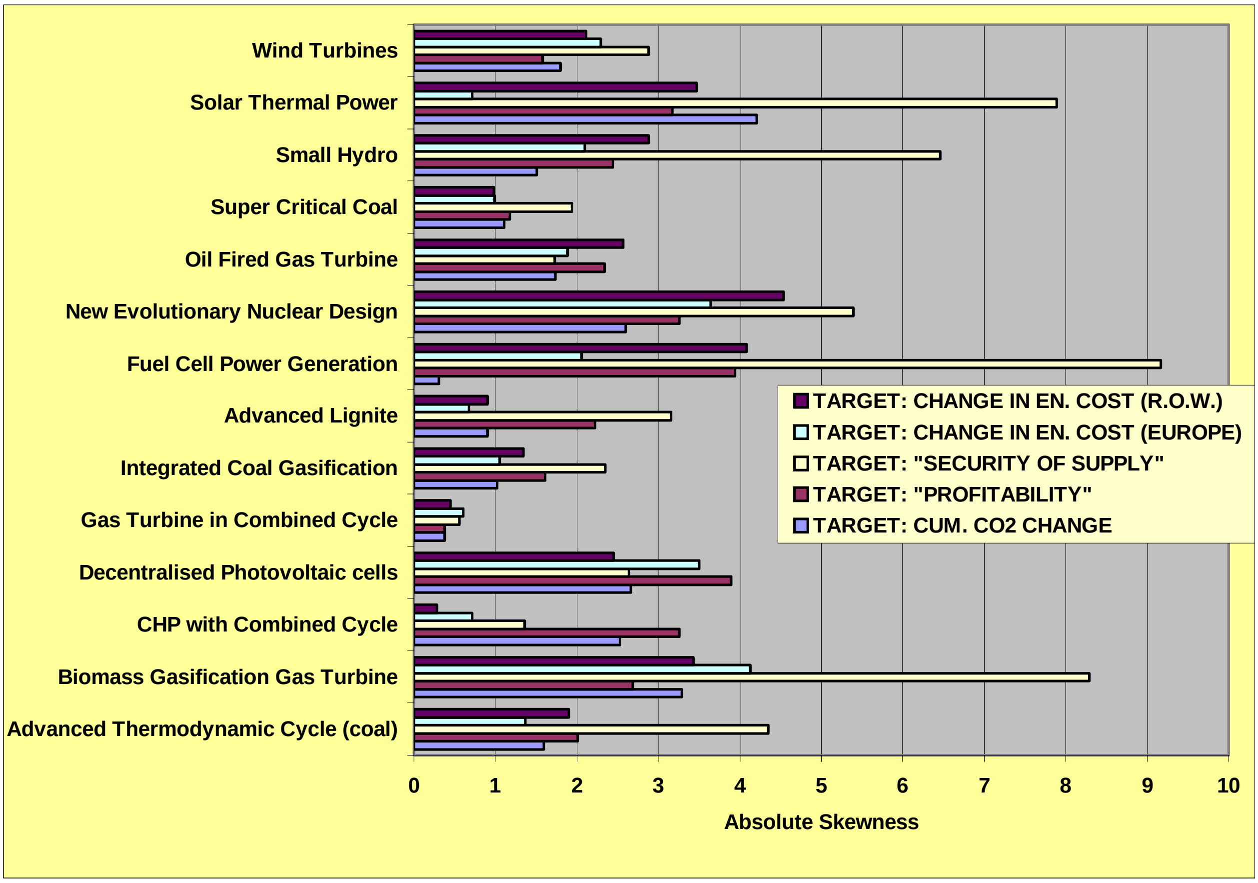
The table above summarises some key PROMETHEUS results on the impact of R&D shocks applied to a selection of energy technologies with respect to the above specified R&D objectives. Starting with the profitability measure, the results indicate that the impact on this target in general presents high volatility across various technologies. The gas and wind turbines present the highest profitability, followed by the super critical coal, the integrated coal gasification and the decentralised photovoltaic cells to a lesser extent. The solar thermal power also appears highly profitable but with relatively high variability. The resulting figures show that for every € invested in "wind turbines R&D" over 22€ extra will be earned. Correspondingly, for every € invested in the "gas turbine R&D", over 10€ extra will be earned. In all, from an R&D policy point of view, renewable technologies seem to be relatively favoured, followed by gas, coal and PV.

In terms of impact on cumulative CO2 change, wind turbines display the highest productivity of R&D. Compared to the performance of wind turbines, the Gas turbine in combined cycle displays half the productivity but one third of the variability as measured in terms of standard deviation. Biomass gasification also appears highly productive but with very high variability. Turning to other renewable technologies, the solar thermal power exhibits a restricted impact accompanied with relatively large variability. In terms of impact on security of supply, coal technologies display the lowest variability relative to their mean impacts. In particular, super critical coal displays the optimal relation, with medium variability but more than double the impact of any other productive technology. R&D on integrated coal gasification and biomass gasification gas turbine technologies present almost equal security of supply benefits; the former technology however performs at less than half variability levels, thus displaying a more consistent behaviour. As regards renewable technologies, wind turbines demonstrate the highest productivity in terms of security of supply, which is somehow moderated by the corresponding relatively high variability. With respect to the impact on energy cost reductions to the consumer, R&D investment in the gas turbine in combined cycle produces the highest cost efficiency, followed by the biomass gasification gas turbine, the wind turbines and the super critical coal to a lesser extent.

As a broad conclusion of the analysis, all impacts for all targets fail the normality test. This is mainly due to pronounced skewness, itself seemingly related to the two-factor learning curve specification. Under favourable conditions involving a high response to R&D coupled with reasonable learning by doing effects and a general environment favouring a particular technology (e.g. presence of a high carbon value or its complete absence depending on the technology) it tends to make very significant impacts (sometimes equivalent to "sweeping the board") when as in most cases impacts are rather moderate. As the graph below demonstrates (Figure 6) this skewness is particularly pronounced for new technologies like solar thermal power plants, the new nuclear design, fuel cell generation and biomass gasification gas turbines which currently make little or no contribution to power generation and are marked by lacklustre average performance in the reference case and therefore have potential for exceptional performance under exceptionally favourable circumstances. On the other extreme lies the gas turbine in combined cycle technology, which is in any way the winning power technology on average. Among targets skewness seems to be most pronounced with regard to impacts on security of supply seemingly mainly due to the rather "volatile" definition of this target.

The correlation matrices appear to be surprisingly sparse in view of the stronger correlations identified in the broad energy aggregates. This sparseness is particularly pronounced for the “profit” target but also for the energy costs to the consumer targets. Impacts on security of supply on the other hand display stronger correlations. In general the clean coal technologies have more closely correlated impacts since they depend on similar configurations for making substantial inroads. A major source of independence of impacts despite the strongly correlated environment seems to be the variation in the parameters of two factor learning curves. In particular learning by research parameters are marked by relatively high variances (tending to dissociate the outcome from the general energy environment), pronounced negative co-variances with their respective learning by doing parameters but so far total independence from TFLCs of other technologies. This latter feature is clearly unrealistic at least for some of the technologies, for example those involving gas turbines which are likely to benefit from generic spillovers.

Figure 6: Skewness of distribution of R&D impacts



7. Exploring R&D Budget Options using ISPA

The main thrust of the research undertaken within the SAPIENT project has been the construction of the ISPA tool and its use for energy R&D budget exploration. In principle such use would implicate interactions with decision makers involved in R&D policy formulation. However the SAPIENT methodology is essentially still experimental and direct involvement of policy makers at this early stage risked becoming a confusing and inconclusive exercise. The exploration was therefore carried out by project partners and in particular the project co-ordinators in order to familiarise themselves with the properties of the tool and evolve methods for its interactive use in preparation for future applications. The section below summarises some of the experiences gained and results obtained in such proxy exercises.

The first task in ISPA utilisation is the definition of a feasible set. This consists in specifying for each objective retained thresholds for the impact of R&D and minimum probabilities that they will be exceeded. For meaningful exploration the initial set should be sufficiently large to allow for contrasting solutions as the exploration proceeds by increasing levels of ambition concerning specific targets. At the same time it should not be so large that it renders most of the probability constraints redundant (signifying that the given objective is completely inoperative in the exploration).

For an initial set of exploration exercises the feasible set was defined as follows:

The probability that the R&D budget results in:

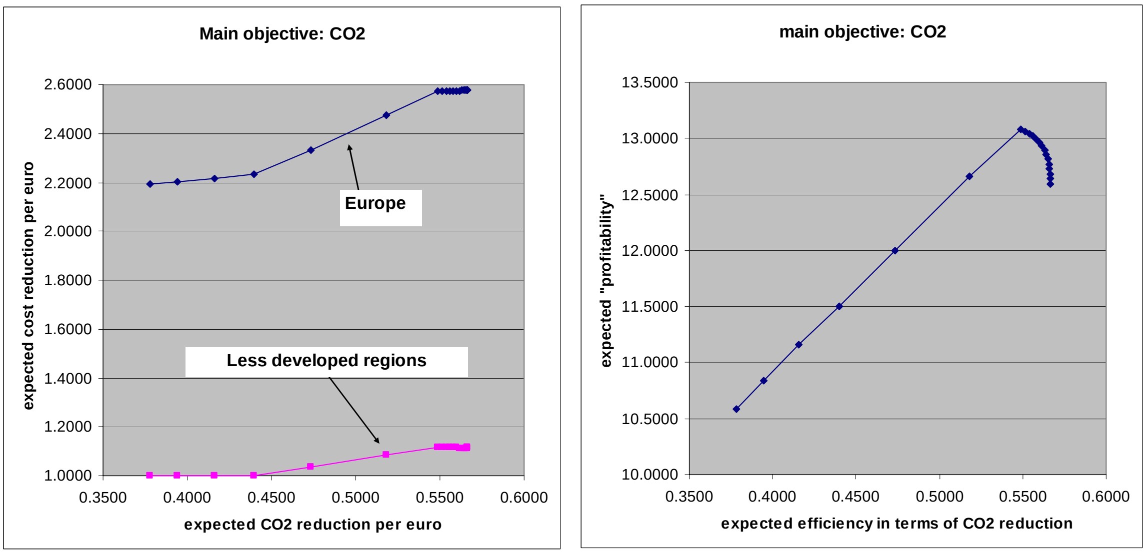
- A reduction of cumulative CO2 emissions should be greater than 90%
- An improvement in security of supply should be greater than 50%
- A reduction in the EU annual energy bill in 2030 of one Euro for every Euro spent in R&D now should be greater than 90%
- A reduction in the annual energy bill in less developed countries in 2030 of one Euro for every Euro spent in R&D in the EU now should be greater than 50%
- A profit rate (as defined within the SAPIENT project) greater than 200% should be more than 95%

7.1. Initial set of R&D exploration exercises

For the initial exercise profitability (a crucial but more conventional target) was used as the main objective while the sustainable development objectives operating via the constraints. The profitability threshold was raised in small steps from 200% to 1280% (beyond this value the character of the solution changed from hedging to “gambling”). Clearly as the profitability threshold is raised the probability of exceeding it declines: slowly at the beginning (from 98% for a threshold of 200% to 90% for a threshold of 560%) and more precipitously as the ambition increases (from 80% for a threshold of 800% to 60% for a threshold of 1150%). At low levels of profit ambition the constraint on energy costs in less developed countries is binding when as beyond a threshold of 550% the constraint on energy costs in the EU becomes increasingly important to the point that the solution virtually stabilises in an effort to satisfy it. At a low level of ambition the portfolio is diversified with many technologies with relatively modest profit prospects in the horizon to 2030 (fuel cells for power generation, integrated coal gasification- ICG and solar thermal power) maintaining budget shares through statistical independence of their prospects contributing to the maximisation of the probability that the profit threshold will be exceeded. ICG is a case of particular interest attracting more than 20% of the budget at low ambition levels because apart from profit hedging it facilitates the satisfaction of the probability constraint on the energy costs in third countries. Beyond a level of ambition of 550% all the modest profit prospect options are eliminated and the budget concentrates on four technologies: GCC (gas turbines in combined cycles) with allocations of over 55% wind turbines (over 25%), biomass gasification (10% to 13%) and supercritical coal (7.5% to 5.5%). Supercritical coal (with modest profit prospects) plays the role of facilitating the satisfaction of the cost to the EU requirements hedging against high hydrocarbon prices. Biomass gasification (BGT) steadily gains share as the ambition is increased because it is characterised by relatively high albeit more uncertain profit prospects.

Placing cumulative CO2 reduction as the main objective the threshold measured in terms of tonnes per R&D euro (99) was raised in small steps from zero to 0.54 (beyond this value the character of the solution changed from hedging to “gambling”). Unlike the case of the exploration using profitability as the main objective the security of supply constraint is binding for the whole range of emission reduction thresholds. This means that all solutions obtained are neutral with respect to energy security (they maintain a 50% probability of a deterioration in energy security as defined within SAPIENT). The energy cost to the EU consumer constraint is also operative for thresholds higher than about 0.1 tonnes per euro. The combined effect of these constraints is the maintenance of supercritical coal as an R&D option for hedging purposes alongside BGT, wind and GTCC. An interesting finding within this set of exercises has been the broad synergy between ambition on CO2 reduction on the one hand and profitability and consumer cost reductions on the other as long as the threshold for CO2 reduction was maintained below 0.18 tonnes of CO2 for each R&D euro spent. This synergy is illustrated in the pay-off curves presented below.

Figure 7: Pay-off curves on the CO2 reduction objective.



It should be noted that values refer to expectations and are different than the thresholds which represent minimum requirements associated with a given probability. For example the first value of the threshold for productivity in terms of CO2 reduction is zero but the expectation associated with it is just under 0.38 tonnes per euro spent on R&D. An inspection of the pay-off curves indicates that there is a clear discontinuity around the seventh point illustrated. Beyond this point, for example the average impact in terms of CO2 reduction can be improved only at the expense of expected profitability (though the drop in the latter is initially rather small). Likewise the expected impact on energy costs does not increase beyond the seventh point. It could be argued that the drops in profitability are small enough to justify a higher impact in terms of CO2 but it should be noted that the gains themselves are very modest and are additionally associated with higher risks. It is for such reasons that such discontinuities on pay-off schedules indicate good candidates for compromise solutions (no or low regret solutions). The budget allocation on the seventh point on the graphs is 55% for GTCC 24% for wind 17% for BGT and 4% for supercritical coal. It is worth noting that a large share goes to a technology which is more or less neutral in terms of CO2 (relatively low emissions with large and reasonably secure market penetration prospects) a relatively new renewable source (wind) which is poised to gain considerable market share if its technical and economic characteristics permit it, a more speculative renewable technology (BGT with large but rather uncertain potential) and a clean coal technology for hedging against supply insecurity and high energy costs. The expected productivity of R&D is .59 tonnes per euro while the probability of exceeding 0.18 tonnes per euro is maximised and stands at 98.7%.

In setting the other targets at the main objective position some of the constraints tended to dominate as follows:

- The CO2 reduction probability constraint when the cost to the European consumer was the main objective (for thresholds of less than two euro reduction for every euro of R&D spent)
- The profitability and security of supply probability constraints when the cost to the consumer of less developed regions was the main objective
- The CO2 reduction and the cost to the consumer of less developed regions probability constraints when security of supply was the main objective

The table below summarises the approximate optimal budgets obtained in this set of exercises:

Table 4: Approximate optimal budgets

Main Objective	Cost to EU Consumer	Cost to Consumers in Less Dev. Regions	Security of Supply
Biomass Gasification	10%		12%
Gas Turbine Combined cycle	42%	68%	34%
Supercritical Coal	38%	25%	39%
Wind Turbines	10%	7%	15%

7.2. A second set of R&D exploration exercises

A general remark arising from all the exercises as reported in the previous section was the quasi dominance of gas turbines in combined cycles for R&D funding. This group of technologies is expected to dominate new plant markets both in developed and developing regions in the ISPA horizon to 2030. Improvements in this technology could increase competitive advantage and hence provide very good profitability prospects. This market dominance also means that expected impacts of improvements on electricity consumer costs are very important especially in less developed regions where most of the capital turnover and hence renewal is expected to take place. With regard to CO2 though GTCC produces emissions it does so at a lower rate (per KWh) than almost all of the other fossil fuel options. It is only in terms of security of supply that this technology is potentially disadvantageous as it encourages gas use leading to vulnerability to supply disruptions (hence the smaller budget shares obtained when security of supply was given priority as an objective). It should be noted that despite this dominance diversification is an integral ISPA characteristic through the mechanism of hedging on the main objective itself but also the probability requirements on the other objectives. This diversification notwithstanding, it could be argued that a technological option with such market potential would anyway attract sufficient private R&D to ensure considerable improvements. Taking a public R&D perspective a second set of exercises using ISPA was performed excluding the GTCC option.

In attempting to carry out the policy exploration with this modification a series of problems were encountered regarding feasibility or sufficient size of the feasible region to enable meaningful threshold variation. The technology that was excluded (GTCC) played a key role in terms of profitability and energy cost reduction and some diminution in the ambition concerning these objectives seemed necessary. After a series of test runs the feasible set for the new series of exercises was defined as follows:

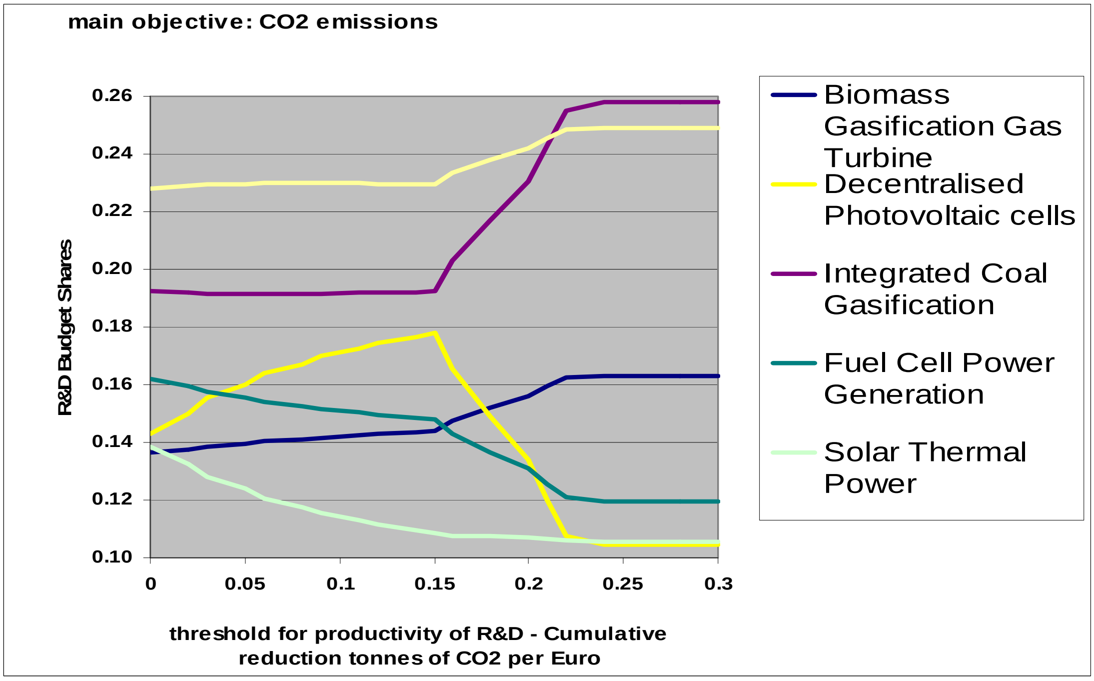
The probability that the R&D budget results in:

- A reduction of cumulative CO2 emissions should be greater than 90% as in the first set of exercises
- An improvement in security of supply should be greater than 50% as in the first set of exercises
- A reduction in the EU annual energy bill in 2030 of one Euro for every Euro spent in R&D now should be greater than 50% (instead of 90% in the first set of exercises)
- A reduction (just any reduction) in the annual energy bill in less developed countries in 2030 should be greater than 50%
- A profit rate (as defined within the SAPIENT project) greater than 50% (instead of 200% as in the first set of exercises) should be more than 95%

The modified set represents considerable downgrading in terms of profit expectation and hedging. Even so the relaxed profit constraint was found to be binding in all cases where the other targets were placed as main objectives and was even operative when increasing the profitability threshold beyond 400%: maximising the probability of exceeding this threshold was in conflict with the maintenance of a 95% probability of exceeding the revised "minimum" of 50% "profitability".

As could be expected the removal of a dominant technological option and the changes in the feasible area has resulted in radically different budget allocations for all exercises examined. In general more technologies were retained even at high levels of ambition. Furthermore the budgets were more balanced in that there emerged no dominant option. As an example the case of the CO2 reduction target as the main objective is discussed briefly below. The graph presents the budget allocation as the threshold (level of ambition) regarding CO2 reduction is raised up to 0.3 tonnes per euro of R&D.

Figure 8: Budget Allocation given a threshold regarding CO2 reduction.



It is noteworthy that six technologies figure with shares of more than 10% throughout the range of thresholds. There appear to be three phases in the allocation as the threshold is increased. The first (up to a threshold of 0.15 tonnes of CO2 per euro) is characterised by a high degree of diversification. Photovoltaic power (with relatively small expected impact to 2030) and fuel cells (with more uncertain prospects and a less than clear cut impact on CO2) are maintained at high budget levels for hedging purposes. The same is true of solar thermal power though its clearly smaller prospects mean that its share starts declining even for modest increases in CO2 reduction ambition. From 0.15 to 0.22 tonnes per euro there is a rapid reversal. Wind power and biomass increase their share to facilitate meeting the more ambitious target. The profitability constraint which is operative throughout the exercise meaning that this increase in renewable energy funding must be accompanied by an increase in integrated coal gasification (ICG) funding. This seeming paradox is explained by the fact that ICG is potentially the most efficient (and hence lowest emitter) among the clean coal technologies considered and at the same time its profitability prospects are negatively correlated with the prospects of renewable power technologies that are rising in this phase. Photovoltaic power and fuel cells must give way to allow for the above developments. Beyond a threshold of 0.22 tonnes of CO2 per euro the constraint on the minimum probability requirement becomes operative: any further increase in BGT or Wind (not to talk of ICG) increases the risk that the CO2 objective collapses (the probability that the R&D budget results in an increase in cumulative CO2 emissions would be higher than the stipulated 10%). The solution therefore stabilises with ICG retaining 26%, wind turbines 25%, BGT 16%, fuel cells 12% and Solar thermal and photovoltaic power 10.5% each.

7.3. Summary Overview of Results

A summary view of the budget results arising from the whole range of exercises leads to some robust observations on the different power technologies as candidates for R&D funding:

- Some technologies that were included as candidates failed to attract any funding irrespective of the target that was placed as the main objective or whether the GTCC option was excluded. These were:
    - CHP the technical / economic characteristics and general prospects of which are closely correlated with GTCC. When the latter was excluded and the profitability constraint became binding throughout CHP was excluded because of lower profit prospects than all the other technologies included.
    - Advanced Thermodynamic cycle (hard coal) and Advanced Lignite the prospects of which are strongly correlated with the other clean coal technologies (ICG and SCC) while their expected performance was substantially inferior on every one of the objectives explored.
    - New Evolutionary Nuclear design because of poor learning by research characteristics: according to the Technology Database this technology has attracted considerable R&D effort while displaying little improvement in economic performance, a fact that is reflected in the learning curve relationship used for the analysis.
    - Oil fired gas turbine because of relatively poor profitability performance and negative expectations with regard to all other targets
- GTCC (when included) dominated the budget for reasons exposed in an earlier paragraph. Its share was highest in all cases and ambition levels with the exception of the case where priority was given to security of supply when it was overtaken by supercritical coal but still maintained close to one third of the budget.
- Clean coal technologies featured strongly in almost all the cases examined including those that gave priority to CO2 reduction. Their prospects being independently or negatively correlated with those of renewable and gas based power options their funding constitutes a major hedging instrument especially with regard to meeting binding probability constraints on secondary objectives. Of the two technologies featuring in the solutions ICG has more attractive prospects in terms of profitability (higher learning potential) and CO2 (higher efficiency potential) while SCC is more effective in terms of the other objectives because of its higher expected market impact especially in less developed regions. Consequently ICG dominates the clean coal choices when priority is given to the CO2 reduction or profitability. SCC dominates when energy cost to consumers in LDCs is set as a priority. In all other cases its shares are markedly lower in cases where GTCC is excluded because of the importance of the profit probability constraint that characterises them.
- The key renewable power sources that attract funding in the exercises carried out are wind and biomass gasification. In the absence of GTCC they figure with high percentages whatever the target that is set as the main objective and in most cases they do not crowd each other out as the level of ambition regarding a target variable is modified. In the presence of the GTCC option in general they tend to get somewhat lower shares and very low funding when energy costs to the consumer are set as the main objective.
- Photovoltaic cells (DPV) and fuel cells represent the more speculative options in the portfolios explored. Their prospects to the 2030 horizon are rather limited and there is considerable uncertainty surrounding them yet they offer vehicles for diversification once the basic risk conditions are satisfied. In the presence of the GTCC option they are almost completely crowded out but in the second set of exercises one or the other or even both featured in the solution even when high levels of ambition regarding the objectives were set. DPV was particularly favoured when security of supply was given priority while fuel cells attracted more funding when energy costs were the dominant concern. In almost all cases these two technologies acted antagonistically crowding each other out as the level of ambition regarding a target variable is modified.

The table below summarises the ranges for the budget shares attributed to the different technologies for both sets of exercises.

Table 5: Ranges for the budget shares attributed to the different technologies

Technology share (in %) of budget over the whole range of ISPA experiments Main objective:		Gas Turbine in Combined Cycle (GT	Wind Turbines	Biomass Gasification Gas Turbine (B	Solar Thermal Power (SPP)	Integrated Coal Gasification (ICG)	Super Critical Coal (SCC)	Decentralised Photovoltaic cells (DP	Fuel Cell Power Generation
CO_2	*(incl. GTCC)*	50 - 55	13 - 24	9 - 26	0 - 13	1 - 14	-	1 - 5	-
	(without GTCC)	-	23 - 25	16 - 22	10 - 14	19 - 26	-	10.5 - 18	12 - 16
Profitability	*(incl. GTCC)*	50 - 57	14 - 26	6 - 14	0 - 5	0 - 23	0 - 7	-	0 - 3
	(without GTCC)	-	19 - 27	11- 13	11 - 13	27 - 29	-	9 - 14	11 - 16
Energy cost to consumer (Europe)	*(incl. GTCC)*	42 - 67	4 - 9	8 - 10	-	-	20 - 38	-	-
	(without GTCC)	-	25	15 - 16	14	26	-	6	13
Energy cost to consumer (Rest of the World)	*(incl. GTCC)*	68	7	-	-	-	25	-	-
	(without GTCC)	-	18 - 36	11 - 14	15 - 23	25 - 28	39	0 - 6	13 - 21
Security of Supply	*(incl. GTCC)*	34	15	12	-	-	39	-	-
	(without GTCC)	-	22 - 24	11 - 15	14 - 16	20 - 30	0 - 5	17 - 26	0 - 2