SYSTEM ANALYSIS FOR PROGRESS AND INNOVATION IN ENERGY TECHNOLOGIES FOR INTEGRATED ASSESSMENT

Research Project DG RES, 5th Framework Programme

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–FINAL TECHNICAL REPORT–

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PART 1

–PUBLISHABLE FINAL REPORT–

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Athens, December 2005

EXECUTIVE PUBLISHABLE SUMMARY–

Executive Publishable Summary

1. Objectives

The SAPIENTIA project addresses the issue of energy systems analysis by considering driving forces that influence energy technology improvement and in particular the role of R&D in inducing and accelerating it. The project's major ambition is the extension of technology dynamics analysis to a point where it can serve directly in support of R&D portfolio exploration. The analysis covers some of the most important energy technologies that are candidates for community R&D support, incorporates learning processes and technological spillovers and considers a wide range of R&D policy objectives including traditional economic, environmental and a selection of indicators addressing the very topical but often intractable aims of Sustainable Development. Taking into account that R&D strategy evolves in a context of uncertainty, the project undertakes the measurement of interconnected risks in order to incorporate them in a decision support tool designed to assist in the quantitative and systematic exploration of R&D options.

2. Description of Work

A major accomplishment of the SAPIENTIA project has been the construction of an information base containing time series on technical-economic characteristics, energy-efficiency performance, capacity installation and availability as well as public and business R&D directed at the improvement of almost 50 key energy technologies. The resulting unique information set serves as a suitable sample for the econometric estimation of the technology dynamics module, which relates technological improvement to R&D and technology uptake. Information on the system-related aspects of technologies and particularly the characterisation of technological affinities has facilitated the inclusion and analysis of technological spillovers, which can magnify the impacts of R&D actions aimed at one technology but benefiting a number of others. To render policy exploration more relevant to current R&D policy concerns a set of measurable Sustainable Development objectives has been selected, covering GHG emissions and concentrations, temperature change, security of supply, transportation (urban environment), energy costs to consumers and regional imbalances. All models participating in SAPIENTIA were developed, re-specified and extended to incorporate the technology dynamics module and the entire chain from an R&D action to its impact on the selected sustainable development indicators. The effectiveness of R&D policy is by its nature subject to uncertainty. This uncertainty itself has a strategic importance in portfolio selection. In order to address the various risks associated with technological improvement, market penetration and impact on Sustainable Development indicators the PROMETHEUS stochastic model has been extended and applied in order to provide probability distributions of the impact of R&D directed at specific technologies on the sustainability indicators. Variants of the learning mechanism developed within SAPIENTIA were introduced in PROMETHEUS, the world simulation model POLES and the perfect foresight models: ERIS (world, very long term), GMM (Global, Multi-regional MARKAL) and TIMES-G3. Implementation in perfect foresight models presented specific challenges in overcoming lock-in effects.

After some harmonisation of assumptions (including future climate change policy and public and private R&D effort) model generated baseline and R&D policy scenarios have been developed and compared. Two R&D Scenarios, designed to assess the importance of R&D in influencing the energy system towards sustainability, have been defined and implemented using the models. The overall analysis within SAPIENTIA indicates that R&D is broadly a cost effective way of addressing a large number of SD (Sustainable Development) objectives. Some SD concerns however necessitate large scale changes and R&D alone cannot make a major impact. A certain amount of re-direction of Government energy-related R&D could prove effective in pursuit of sustainability on many fronts. It could also prove a fine balancing act because of important secondary effects.

The PROMETHEUS stochastic model has provided the expected impacts and their variance-covariance matrices to be used in constructing ISPA, the policy integration tool used to perform Integrated R&D Policy Exploration. ISPA 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. Diversified and robust solutions emerge, taking into consideration multiple objectives, synergies of R&D actions and the structure of uncertainties.

3. Exploitation Plans

The methodology developed within the SAPIENTIA project has wide potential applications in R&D strategy elaboration. The resulting information base (TECHPOL) can form the basis and the framework for further studies within modelling projects involving specialised issues like the possible technological characteristics and penetration of hydrogen related technologies. The ISPA Policy Integration tool has numerous applications in a great variety of energy/environment multi-criteria decision analysis in a stochastic context. The SAPIENTIA project has delivered advanced versions for all participating models that incorporate endogenous technology progress and can thus provide a more complete and realistic representation of the energy system opening the way for improved energy systems analysis.

–PUBLISHABLE SYNTHESIS REPORT –

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Introduction

The SAPIENTIA project addresses the issue of energy systems analysis by considering driving forces that influence energy technology improvement and in particular the role of R&D in inducing and accelerating it. The project's major ambition is the extension of technology dynamics analysis to a point where it can serve directly in support of R&D portfolio exploration. The analysis covers some of the most important energy technologies that are candidates for community R&D support, incorporates learning processes and technological spillovers and considers a wide range of R&D policy objectives including traditional economic, environmental and a selection of indicators addressing the very topical but often intractable aims of Sustainable Development. Taking into account that R&D strategy evolves in a context of uncertainty, the project undertakes the measurement of interconnected risks in order to incorporate them in a decision support tool designed to assist in the quantitative and systematic exploration of R&D options.

SAPIENTIA is the natural continuation of the SAPIENT project (already completed within the Fifth Framework Programme) whose main achievement has been the demonstration of a way for building a tool for integrated policy assessment. The approach has proved to be fertile providing useful insights for quantitative R&D policy exploration in pursuit of multiple objectives in the presence of uncertainties. SAPIENTIA concentrates on the decision support aspects of SAPIENT and in this sense is much more focused in scope. It also expands significantly the scope by introducing more technologies (candidates for R&D support), describing more fully and operationally spillovers between technologies, enlarging the set of objectives, expanding the policy exploration exercises to the longer term, addressing issues of the efficacy of R&D and Demonstration (D&D) and extends and synthesises technology dynamics results in order to make them useful for actual R&D budgeting policy exploration.

The work presented in SAPIENTIA has been structured around the consolidation and further elaboration of the recent advancements of research in energy systems analysis regarding the dynamics of technical change. In SAPIENTIA, scenarios, cost evaluations and policy assessment are performed using advanced models, which integrate the effects that RTD policy exerts on technology progress. Previous research has shown that the consideration of such a mechanism has considerable implications on shaping the policy, the evaluation of costs and the assessment of the potential of technology development in the markets. Resulting expertise has shown that energy and environmental (especially climate change) strategies have to be substantially reconsidered when evaluated in the presence of induced technological change.

The project delivers quantified information and analysis regarding the system-wide aspects of key energy technologies (both in power and non-power generating sectors) in the framework of the interplay between energy and RTD policy, policy instruments, sustainable development targets (global warming, security of energy supply, ecosystem effects, competitiveness etc.) and technological improvement. Moreover, the project goes one step further to provide results on RTD priorities, portfolio allocation, innovation policy, analytical and quantified results which illustrate the mechanisms of induced technological progress and energy and emission projections for the EU and the World. The latter includes evaluations of impacts on sustainable development under liberalised energy markets for the longer term (up to 2050).

Objectives and Strategic Aspects

Technological change is widely recognised as a major driver of economic growth. In recent years also the notion has developed that targeted technological development is one of the main means in an increasingly liberalised world economy to reconcile economic ambitions with 'externality' considerations such as environmental objectives and the pursuit of Sustainable Development in general. This implies that the assessment of future trajectories of energy systems is particularly meaningful for policy analysis when it takes into account context-specific (i.e. induced) technological progress. Rather than taking characteristics of existing and emerging technologies as given, their development should be considered as a function of dedicated R&D and market deployment under varying external conditions.

Energy systems analysis can assist R&D strategists in exploring R&D options. To provide such decision support insights, energy systems analysis tools must be equipped with mechanisms describing causality chains leading all the way from a certain R&D action to the impacts on targeted objectives. Such chains can be complex involving many interactions and certainly must address issues of technological spillovers, which can magnify impacts of R&D actions aimed at one technology but benefiting a number of others.

The above considerations have led to an increasing need to model the dynamics of technical change by incorporating appropriate mechanisms in detailed energy system models. In exploring the role of R&D and energy policy, the concept of learning or experience curve is employed, incorporating learning attributed to research effort and learning arising from the experience gained through technology take-up. The learning or experience curve reflects the fact that 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.

SAPIENTIA 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 exploring R&D strategies in pursuit of such objectives. The project makes extensive utilisation of existing detailed models which describe the energy system in its considerable complexity and thus 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 the present project develops tools that synthesise these mechanisms while serving as compact vehicles for performing real R&D policy exploration exercises.

The methodology recognises two important characteristics of the R&D budgeting process. First that it evolves in a context of multiple objectives and second that it operates under uncertainty. Such uncertainty arises not only from the inability to predict the direct impact of R&D action but also from a host of other factors including uncertainty over parameters, key developments shaping the future economic conditions, future policy, political events and natural resource endowment. In order to support decisions an attempt was made to measure these uncertainties and incorporate them in a strategic analysis framework.

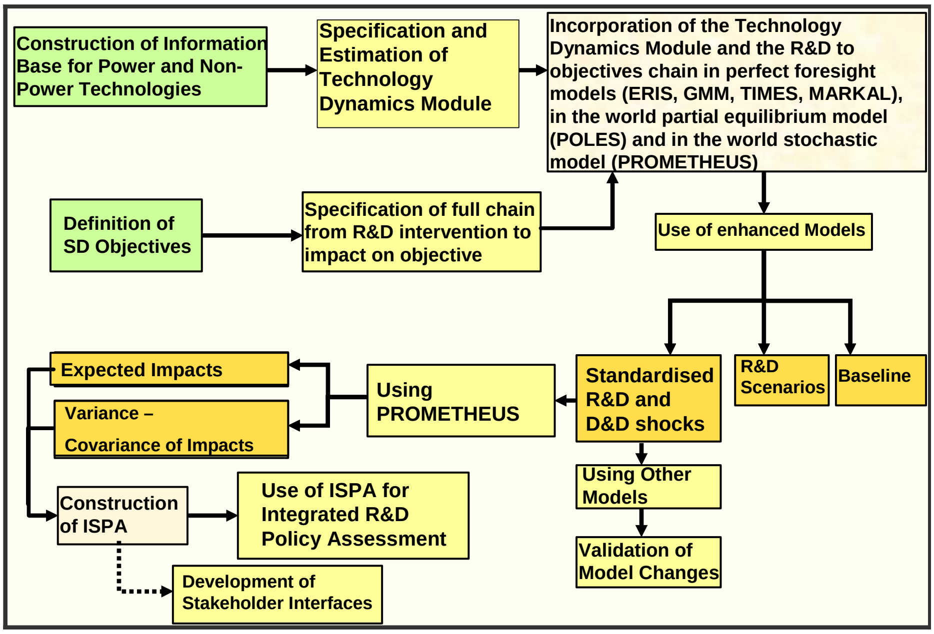
- Overall, SAPIENTIA has engaged in a series of ambitious scientific objectives, which constitute a clear advancement in the domain of energy systems analysis and modelling. These can be summarised as follows:
- Update existing data, collect new data and estimate numerical relationships that link technology improvement with investment and public and private R&D spending, particularly as regards non-power generating technologies, and describe more fully and operationally spillovers between technologies.
- Extend and refine a decision support tool that explores 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.
- Extend the scope of existing large-scale energy system models so as to incorporate specific sustainable development indicators and integrate model results into the decision support tool.
- Extend deterministic and stochastic energy models to perform policy exploration exercises for the longer term (i.e. up to 2050).
- Address the issues of research versus demonstration in specific technologies.
- Consolidate into the operational versions of the large-scale energy models, past developments on the incorporation of endogenous (induced) technology improvement mechanisms.
- Co-ordinate the work from, and promote the synergies between, different energy models that differ in their methodology and the regional coverage.

Scientific and Technical Description of the Results

SAPIENTIA is a very tightly designed project leading to very specific outcomes in the form of R&D policy exploration using the extended Integrating System for Priority Assessment (ISPA) tool involving proxy decision analysts. The work is organised around various sections covering distinct research needs contributing individually to the overall integration which was performed in the final stage of the project. The analysis draws from a very diversified set of areas of expertise involving information collection, statistical estimation, substantial model building and modelling extensions (to a considerable number of seemingly unrelated models incorporating different mechanisms and philosophies) that apart from serving the main objective of the project, have also provided useful insights on the dynamics of technical change in a period of increasing sustainability concerns.

The following table presents an overview of the methodology applied in the SAPIENTIA project:

SAPIENTIA Project Overview



A major accomplishment of the project and prerequisite for all subsequent work has been the construction of an information base for power and non-power related technologies and the collection of technical-economic and R&D expenditure data for the specification and estimation of the technology dynamics module, which relates technological improvement to R&D and technology uptake. A set of measurable Sustainable Development (SD) objectives has been selected and analytical chains were specified leading all the way from a certain R&D action to the impact on SD objective. All models participating in SAPIENTIA (both deterministic and the stochastic model) were developed, re-specified and extended to incorporate the technology dynamics module. After some harmonisation of assumptions model generated baseline and R&D policy scenarios have been developed and compared. This has been essential in order to monitor and validate the model changes by all the modelling teams. The PROMETHEUS stochastic model provided the expected impacts and variance-covariance matrices of the impacts that were used in constructing ISPA, the policy integration tool used to perform Integrated R&D Policy Exploration.

The challenges faced to ensure the credibility of the whole process have been considerable throughout the project. The research agenda constituted from the very beginning a clear advancement in the domain of energy systems analysis and modelling. The following sections summarily report on all the above mentioned tasks undertaken within the SAPIENTIA project.

1. Information Base

A major objective and a prerequisite for all subsequent work in furtherance of the aim of the SAPIENTIA project has been the establishment of the technological background information and methodology that has been shared by all partners in extending their models to cover learning dynamics. The project places emphasis on the complementary or comparative use of the results of different models to drive policy relevant conclusions, accordingly the collection and use of harmonised information on energy technologies has received utmost importance. The first step was to check and harmonise technical-economic data on energy technologies, including information on their purchasing cost, energy efficiency performance, technical/economic life duration, capacity and availability in order to ensure comparability of subsequent results. Furthermore, historical information on the improvement of these economic and technical characteristics of energy technologies that could be attributed to a learning or experience process associated to their use had to be collected and checked for overall consistency. In addition statistical information on public and private expenditures in R&D activities for energy technologies had to be collected in a way as to be able to attribute, albeit approximately, specific expenditures to the different technologies concerned. Existing literature also had to be surveyed on information regarding the prospects of technology improvement in the future in order to indicate a domain for feasibility and realism and provide appropriate benchmarks for the prospects of the technologies retained. Information on system-related aspects of energy technologies had to be collected with particular emphasis on identifying and describing clusters, generic technological progress and spillovers. The datasets thus collected were used in order to carry out econometric estimations of two factor learning curve relations linking energy technology progress to R&D spending and capital accumulation. The resulting causal relationships were essential building blocks for the representation of technology dynamics in all models involved in SAPIENTIA and play a crucial role during the synthesis stage of the project.

The first step involved the identification and characterisation of non-power technologies which are expected to play an important role in future energy systems. Unlike power technologies, which are characterised by a relatively homogenous market and characteristics (power being a common end product), non-power technologies tend to be diffuse in character and have often attracted less attention in terms of characterisation and prospects. Yet they have a crucial role in terms of meeting R&D policy objectives. For the purposes of SAPIENTIA an extensive inventory of non-power technologies with good prospects for improvement has been compiled although data was not as available as foreseen at the proposal stage of the project. The final selection of technologies was made on the grounds of their potential impact on future energy balances, their promise in terms of improvement, their interaction with other technologies including power generating technologies and the interest they have attracted in recent years as candidates for R&D support both in the public and private sectors. The short listed non-power technologies include Hydrogen production and handling technologies (Hydrogen Liquefaction, Hydrogen Electrolysis), CO_2 capture and storage technologies, end use technologies in transport and in building environments (Stationary Fuel Cells, Heat Pumps, Condensing Boilers) and a novel technology (Organic Rankine Cycle).

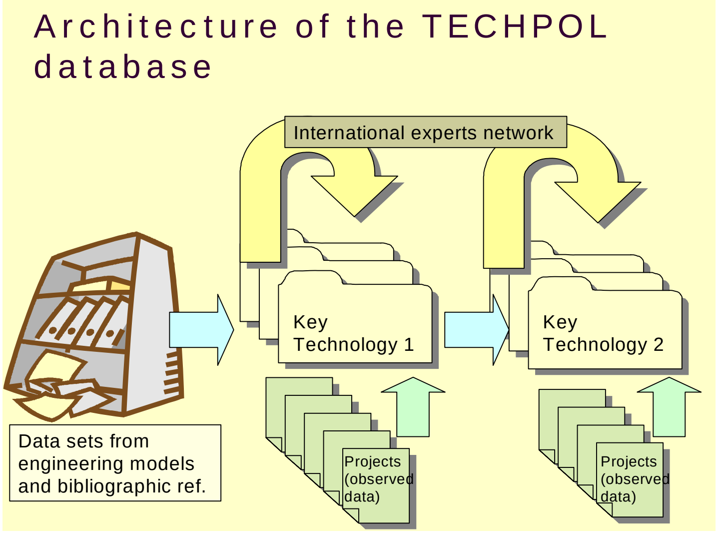
On the basis of the final list of non-power technologies retained in the analysis, the clustering approach developed in the SAPIENT project has been extended to cover both power and non-power technologies and facilitate the inclusion and analysis of spill-over effects. All power and non-power technologies considered in the analysis were categorised by key component and a technology matrix is set up. The resulting clustering matrix retains 11 key technologies already applied in SAPIENT whereas 11 new are added: 4 carbon capture and sequestration, 4 residential end-use (heat demand) and 3 automotive.

The construction of the information base required the collection, filtering and screening of statistical information on the technical and economic characteristics of the technologies retained. To this end, a literature survey has been conducted to obtain information on the past and (expert judgements on) future improvement potential for these technologies and on the behaviour of relevant techno-economic parameters; the information gathered was checked for overall consistency insomuch as these improvements could be attributed to a learning or experience process associated to the use of these technologies. The collection of consistent historical information on these parameters has proved to be particularly arduous and time-consuming as it involved the construction of time-series of a sufficient historical length when no regularly updated information basis exists and data is usually available for a few time periods and often only recent ones. This deficiency was corrected by digging into older studies/surveys which, however, were relatively difficult to locate. Apart from that, different sources often displayed very wide differences in the technical and economic characteristics of what are apparently the same technologies. These were usually due to different definitions (size, the inclusion or not of installation, infrastructural, de-commissioning costs, interest during construction etc). It was however essential to obtain a consistent set, especially as in the course of modelling the different technologies are set to compete against each other. In an effort to overcome the aforementioned inconsistencies, various innovative methods were developed to set up sufficient time series from scarce and incomplete data.

One of the most important accomplishments of the SAPIENTIA project has been the creation of a common database structure on the costs and performance of the new energy technologies considered, called **TECHPOL**. The innovation of the TECHPOL database lies upon the provision of consistent data in order to assess the drivers and inducement factors in the dynamics of new energy technologies. The TECHPOL database gathers a first set of data on new energy carriers (hydrogen) and new technologies (capture and storage, 4th generation nuclear, fuel cells, highly energy-efficient technologies) based on reference papers and reports and on expert assumptions. In order to maximise its reliability, the information acquired was then processed using innovative methods so as to facilitate the comparability of existing data. Comparing existing data has allowed establishing reference values on costs and performance for key power and hydrogen generation technologies including CO_2 capture and storage.

The TECHPOL database has been built on past experience with technology data collection developed during former European research projects (such as SAPIENT). Its aim is to go beyond the selective collection of data which may rapidly become out of date, especially with regard to very new technologies that have not yet reached the market. The idea is to collect information on new technologies on a regular basis in order to improve expert assumptions regarding future costs and performance and to provide a reliable vision of technical change in the energy sector.

Figure 1: TECHPOL Database architecture and data production



The database has been structured in two separate but inter-related sections. The first section contains data observed from past or ongoing specific projects related to new energy technologies whereas the second section incorporates data that does not rely on observation but intends to reflect the costs and performance of generic technologies.

Consequently, the TECHPOL database benefits from a double procedure for the validation of data sets related to key technologies:

- on the one hand, new information coming from ongoing projects and observations is regularly added to the database; after being organised and processed these datasets contribute to the production of reference values;
- on the other hand, the calculated or estimated data corresponding to generic technologies is compared to data used in large energy sector models and validated during an interactive process with modelling teams and technology experts

Through this procedure, the TECHPOL database organises a consolidated interactive process between modellers and technology experts that leads to a clear improvement in the quality of the data sets.

The final synthesis of the database presents analytical data for almost 50 different technologies which belong to the following broad categories:

- Centralised/large scale power generation (includes both fossil and nuclear electricity production)
- Distributed or renewable power generation (includes both small and large renewable power generation units and fossil distributed production systems)
- Hydrogen Production (5 technologies)
- Demand side/transport technologies

To cover the requirements of all participating models, data has been acquired with respect to five main parameters:

- Overnight Investment Cost
- Electrical Efficiency
- Technical Lifetime
- Load Factor
- Variable Cost
- Fixed Operation & Maintenance Cost

To provide a detailed description of technologies and a precise characterisation of the data, the database is also enriched with a wide range of information including:

- Source of Information (primary or secondary)
- Date of Reference
- Type of technology (description, average size/capacity, specific equipments)
- Geographical area (global technology or specific to a region/country)
- Nature of the data.

A variety of sources had to be utilised in order to cover this wide spectrum of data required. Overall, the extensive data collection has allowed the integration of almost 300 different time series for past, present and projected costs of 30 technologies.

As a means to reinforce the quality of the data collected, a complementary tool has also been developed, with the aim to facilitate the comparison of production (for electricity and hydrogen) and transport costs (for road passenger cars) within a harmonised framework. This framework provides a standardized calculation procedure for electricity/hydrogen levelised production costs. It allows visualising the combined effects of different factors that may influence production cost and facilitates a more accurate assumption of the future evolution of key parameters (such as investment cost, efficiency, variable or fixed Operation &Maintenance cost).

Regarding the construction of the R&D expenditure (private/public) database within SAPIENTIA the Government Energy R&D Data Base has been updated to include all new technologies considered. The resulting GERD-DB is an update/revision of the SAPIENT DB with the latest available IEA data. GERD-DB intends to provide a comprehensive view of energy R&D in spite of the uncertainties attached to total spending and categories. It also includes an assessment of H_2 and Carbon Capture and Storage programs, even though a full disaggregation among technologies couldn't be accomplished. This has entailed the survey of a wide variety of publications, the Community Research & Development Information Service (CORDIS) and the US Department of Energy (DOE) energy programmes databases.

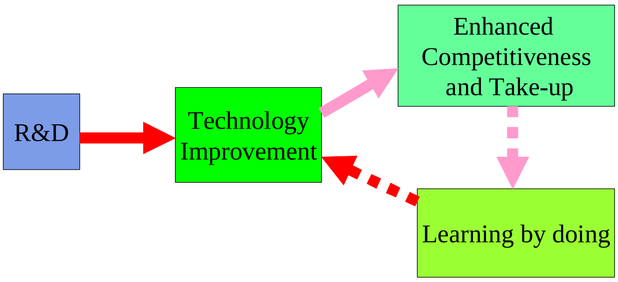
The construction of the R&D expenditure database has been a very challenging and innovative task, which however was expected (and proved) to be very demanding and time-consuming. Considerable difficulties have been encountered especially due (rather surprisingly) to the sparsity and unreliability of historical information on costs of the technologies. Moreover, limited R&D data is available for the infant new technologies and in many cases time series data were insufficient. Sources for Private R&D data in particular have proved to be rather scant; existing data is of strategic value and hence not readily disseminated for public use. In order to obtain even just reasonable estimates, recourse to indirect methods was necessary. These include gross R&D expenditure of specialised companies that are key players in technological development in the relevant domains, patent application data for apportioning such expenditure to specific technologies, and other innovative methodology involving indirect methods depending on relevant indices.

Two Factor Learning Curves

The resulting unique information set serves not only as a suitable sample for estimation and a starting point for model runs, but also represents the state of the art of the SAPIENTIA database for the study and econometric estimate of the Two Factor Learning Curves for some key new energy technologies. The specification and estimation of the two factor learning curve relations for use in the large models as well as in PROMETHEUS is the backbone for meaningful policy analysis in the context of the SAPIENTIA project as they constitute the main vehicle and first step through which R&D actions translate into impacts. Their estimation provides essential stochastic input for the stochastic model (PROMETHEUS) in the form of variance and co-variance of learning by research and learning by doing effects.

The general scheme of the technology dynamics mechanism is presented below:

Figure 2: General scheme of the technology dynamics mechanism



Under this scheme, an R&D action leads directly to technological improvement, which in turn enhances competitiveness of a particular option and leads to increased technology take-up. This latter increase sets in motion learning by experience, which results in further technological improvement, further up-take etc. In this sense, learning by doing acts as an accelerator of the impact of initial R&D effects. Clearly, the cycle contains dampening effects that result in finite overall impacts. This dampening notwithstanding, the inclusion of such mechanisms in models does tend to introduce elements of instability, in particular "lock-in" effects –massive R&D funding on some options may lockout other options that fail to benefit from the learning by experience they could have enjoyed, had such initial R&D infusion not taken place. Models thus become sensitive to initial conditions. On the other hand there is sufficient evidence that this is indeed an accurate representation of the way technical progress has occurred in the past.

Some specific properties have been sought for the specification of the two factor learning curve formulation: the TFLCs should incorporate both learning-by-doing and learning-by-research (which is crucial in order to be able to perform the R&D policy exercises), endogenise as much of the technical progress as possible, constrain to technical possibilities as they emerge from perspective analysis, include “Clustering” as fully as available information allows, take carefully into account initial conditions regarding cumulative R&D and equipment stock and capture as much of the above with as few parameters as possible.

A general algebraic specification has been derived and considerable effort has been devoted to standardise the formulation as much as possible. Some exceptions however were deemed necessary due to specifities of the technologies. As a result, the technologies are classified into five categories, the Cluster Matrix Technologies, for which a cluster matrix is supplied and the general algebraic formulation can be applied, the Stand Alone Technologies, which are orthogonal technologies and do not need to consider clustering, the Perfect Clustering Technologies, the technical and economic characteristics of which are directly related to the corresponding characteristics of other technologies in the same cluster (for example the wind offshore and wind onshore technologies), the On-board storage technologies, (a sub-category of the perfect clustering technologies) that are shared by different types of vehicles and finally the Fuel Cell technologies.

Particular attention was given to the estimation of the TFLCs so as to ensure that apart from statistical fit they also displayed sufficient robustness for use in the wide variety of models and especially that they performed credibly in view of the R&D policy analysis. For the estimation historical time-series for R&D, equipment stock, capital costs and projections of technical and economic characteristics of technologies were used (as derived from the TECHPOL database), projections of installed equipment from the provisional POLES Baseline, projections of public and private R&D by technology elaborated by ICCS/NTUA, and finally cluster information from MARKAL. Clustering of technologies has been incorporated through learning by doing. The learning parameters were estimated by applying Maximum likelihood estimation over the historical period; yet this was by no means the only estimation criterion. All properties sought in the TFLCs specification figured among the objectives of the estimation. In addition, simultaneous equations estimation has also been applied (along clusters) in order to improve estimates and obtain appropriate co-variances of learning parameters. In all, technology dynamics have been estimated for a total of 51 technological options covering power generation, CO_2 capture and sequestration, Hydrogen-related technologies, conventional and non-conventional vehicles and Fuel Cells. Learning parameters were estimated for capital costs, fixed Operation and Maintenance costs, variable Operation and Maintenance costs, efficiencies and CO_2 capture rates.

Particular attention has been paid to the stochastic characteristics of the learning parameters, since they play a crucial role in determining the uncertainties surrounding the impacts of R&D actions that constitute an element for the integrated policy analysis performed at the end of the project. In general, learning by doing and learning by research parameter estimates within a single technology are strongly and negatively correlated, which tends to reduce variability of learning. Also, learning parameter estimates of the same type for different technologies within the same cluster tend to be positively correlated. This implies some uniformity in the stochastic behaviour of the whole cluster. Learning parameters also tend to be positively correlated when the same type of learning coefficient is considered (either learning by doing or learning by research). On the other hand, they tend to be negatively correlated when for example the learning by doing parameter for the capital cost is compared to the learning by doing parameter for the efficiency of the same technology.

Table 1 below provides a classification of technologies with regard to their learning characteristics for capital costs as they emerged from the estimation. From the R&D policy point of view, the potentially most interesting technologies are those on the upper right corner of the table, where the fast and mostly learning-by-research technologies are presented. The technologies characterised by fast, balanced learning (new nuclear and photovoltaics) also have good prospects, as the impacts of R&D investment on these technologies (leading to enhanced competitiveness and take-up) are magnified by learning by doing at presumably no additional cost.

Table 1: Technology characterisation

	Capital Costs		
	Mostly Learning by doing	**Balanced Learning**	**Mostly Learning by research**
Fast Learning	Hydrogen internal combustion engine passenger car	New Nuclear (4th gen.)/ Building integrated PV	Fuel Cell/ Wind turbines offshore/ Post-combustion CO2 capture (Supercritical pulverised coal)/ Pre-combustion CO2 capture (Integrated gasification combined cycle)
Medium Learning	Nuclear (2nd and 3rd gen.)/ Cogeneration from gas/ Post-combustion CO2 capture (Gas turbine combined cycle)	Hydrogen from Biomass Pyrolysis/ Hydrogen from Nuclear High-temperature Thermochemical Cycles/ Hydrogen from Water Electrolysis and dedicated Nuclear power plant/ Pre-Combustion CO2 capture(Coal Partial Oxidation)/ Large Hydro/ Supercritical pulverised coal/ Electric passenger car/	Hydrogen from Coal Partial Oxidation/ Hydrogen from Solar High-temperature Thermochemical cycles/ Oil fired Open cycle gas turbine/ Wind turbines Onshore/ Solar Thermal power plant cylindro-parabolic/ Biomass thermal/ Biomass gasification plus combined cycle/ Hybrid passenger car
Slow Learning	Hydrogen from Gas Steam Reforming (large scale)/ Lignite conventional thermal/ Coal conventional thermal/ On board reformer cost (Natural gas fuel cells passenger cars)/ Hydrogen storage cost (hydrogen fuel cell passenger cars)	Gas turbine open cycle	Hydrogen from Water Electrolysis (baseload electricity from Grid)/ Pre-Combustion CO2 capture (Gas Steam Reforming)/ Integrated coal gasification/ Oil conventional thermal/ Gas conventional thermal/ Gas turbine combined cycle/ Small hydro (<25MW)/ CO2 sequestration

The table above is indicative and should be viewed with caution. The ultimate success of R&D action on a particular technology not only depends on its learning characteristics, but also on the general context defining the market for this technology. This is determined by a host of factors including competition with other technologies, evolution of fuel prices, the intensity or lack of climate policy, overall and regional activity levels that determine the rate of technological renovation etc. This context can be quantitatively examined only through integrated models of the whole energy system.

2. Model extensions in the context of the SAPIENTIA project

2.1. Sustainable Development Objectives

In recent years Sustainable Development issues have been rising high on the political agenda. The SAPIENTIA project assumes that sustainability concerns will form a key element in R&D policy exploration. Considerable effort has been devoted to the identification of appropriate and measurable sustainable development indicators and their link with specific technological options, so that the whole chain from technology take-up to impacts on sustainability can be modelled. The integrated R&D policy analysis that is one of the main results of this project focuses on the evaluation of impacts in terms of the sustainability objectives and the causal relationships defined within this section of work.

For the identification of the appropriate indicators important policy documents related to sustainable development and SD indicators have been reviewed. Particular attention was given to the Communication from the Commission ‘A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development’ (CEC, 2001a) which constituted a proposal to the Göteborg European Council and is largely reflected in the Presidency Conclusions (Göteborg European Council, 2001). Moreover the latest (2003) EU “structural indicator set” used for the Lisbon Strategy was also reviewed. Following the Gothenburg Council, a survey of the results of the activities in the field of sustainable development has been conducted and recent developments within the EU have been examined.

An important task has been the setting of concrete definitions and units of measurement for the proposed SD indicators. The basis for the definitions of the indicators came from the above mentioned EU “structural indicator” set for the Lisbon Strategy. The indicators were subsequently modified so that they could be reproducible by all the models participating in SAPIENTIA.

Initially there has been a maximalist tendency in the selection of measurable objectives (wide number, difficult to measure and/or model indicators considered). As modelling progressed and especially preliminary exercises of applying policy shocks were performed, the list of the SD objectives to be retained had to be re-examined. Given data availability and models’ capabilities, the list of SD indicators quantitatively examined within SAPIENTIA has been defined as follows:

1. **Climate change**

a. *Greenhouse gas emissions*: changes of emissions between 2000 and 2050 (or 2100) separately calculated for CO_2 and CH_4. The global warming potentials used were based on the IPCC TAR report on the basis of a 100-year commitment horizon.

b. *Greenhouse gas concentrations*: changes in the concentrations between 2000 and 2050 (or 2100) separately calculated for CO_2 and CH_4.

c. *Average temperature change*: average change between 2000 and 2050 in terms of degrees Celsius.

d. *Maximum increase of temperature in any decade*: measured in terms of degrees Celsius.

2. **Security of energy supply**

a. *Maximum increase of oil and gas prices in any three-year period*: measured in money terms

b. *Reserves-to-production ratio for oil and gas*: remaining (ultimately recoverable) reserves, expressed in years, calculated separately for oil and gas.

c. *Import dependency*: percentage share of import in total domestic supply, calculated separately for oil and gas in 2050.

3. **Transportation/Urban Environment**

a. *Introduction of low emission passenger cars*: expressed in shares in total park.

4. **European Consumer**

a. *Energy/Electricity cost reduction to consumer*: expressed in Euro

5. **Regional imbalances**

a. *Energy/Electricity cost reduction to consumer in the Less Developed Countries*: expressed in Euro

6. **Market/Economic Objectives**

a. *Market impact*: A measure combining technology penetration and cost reductions

2.2. Extensions of Deterministic Models

In the context of SAPIENTIA, all large deterministic models had to be equipped with the databases and mechanisms necessary for an adequate representation of the developments concerning the expansion of the technology dynamics analysis to cover non-power technologies and of the Sustainable Development objectives. This work, apart from enriching considerably the models involved (POLES, GMM, ERIS, MARKAL), constitutes an essential prerequisite for their use in carrying out the sensitivity analysis (R&D shocks) which provides key input to the R&D priority assessment exercises.

To meet these needs considerable work on model modifications and extensions has been required for all models participating in the project. This implied extensions in their sectoral coverage (to other energy sectors beyond electricity generation), expansions of their technological coverage (to include the technical-economic-environmental characteristics associated with the technologies introduced in the analysis) and a more detailed representation of options in key sectors like transport. At any rate, even models already incorporating most of the technologies retained, needed some interventions aiming at harmonising their characterisation according to the specifications arrived at in the course of the construction of the common information base.

The implementation of TFLCs has posed considerable difficulties to some deterministic large scale energy system models such as GMM, ERIS and MARKAL. These difficulties were mainly due to the very nature of these perfect foresight optimisation models. Conventional NLP solvers can only find locally optimal solutions and global optimisation algorithms are suitable only for very small scale problems. The TFLC through its learning by doing component implies non-convex feasible sets and requires the application of mixed integer programming algorithms, which combined with the non-linearities in the specification of the TFLCs (included to ensure the representation of saturation effects) create a formidable computing challenge. To avoid these difficulties, an indirect two-factor learning curve application has been adopted by these models. A relationship between change in progress ratio and change in the R&D intensity is established outside the model. This can be used to estimate the intensity elasticity of progress ratio and to segregate R&D from the non-R&D effect on the progress ratio and then applied to analyse the R&D impact on technologies.

Behavioural simulation models like POLES can incorporate highly non-linear specifications for TFLCs without creating resolution problems. Even so, the introduction of endogenous learning mechanisms easily leads to the apparition of strong lock-in effects (model instability to small initial changes favouring a particular technology or technological cluster). Therefore, considerable care has been devoted to introduce sufficient stabilising mechanisms to ensure some stability in learning.

2.2.1. Extensions of the GMM and ERIS Models

GMM (Global MARKAL MACRO) and ERIS (Energy Research and Investment Strategies) are multi-regional “bottom-up” energy-systems optimisation models with endogenous technological learning. In the context of SAPIENTIA, these models have been substantially restructured and extended to allow for improvements in the representation of the mechanisms of technological change in the global energy system and in the examination of the role of the energy system in the context of GHG mitigation strategies. The extensions presented here also enhance the capabilities of these models to adequately represent the causal chains from R&D and D&D impact on sustainability indicators.

A clusters approach to the representation of technology learning, which allows different technologies to share a common “key learning component”, has been implemented in both models. Following the ‘key technology’ approach proposed by Seebregts et al. (2000), key components have been introduced in the areas of electricity generation, synthetic fuel production (alcohols and hydrogen), CO_2 capture in fossil and biomass-based power plants, hydrogen production and passenger cars. Besides providing a mechanism to capture interactions between related technologies, the clusters approach allows extending the number of technologies in which learning takes place while keeping the computational complexity at a reasonable level.

In the clusters approach implemented within GMM it has been assumed that there are full spillovers between technologies belonging to the same cluster and that technology learning takes place at the global scale. Learning curves are implemented only for investment costs of the key components. For all the key components, a so-called ‘floor cost’, i.e. a minimum cost level at which the learning process ceases has been introduced in order to avoid unrealistic cost reductions, according to the guidelines and values agreed upon within SAPIENTIA.

The representation of the passenger transportation sector in the GMM and ERIS models has been further disaggregated and expanded in order to allow the examination of the impact of specific technologies of interest in the passenger car sector. The transportation sector in these models was originally conceived as an aggregate sector where generic technologies were used to mimic final-energy use. The new representation divides the transport sector into three sub-sectors, namely passenger cars, air transport and other transport. For the passenger car mode, a relatively detailed technology representation is introduced. In the other two sectors, a simplified representation has been chosen with generic technologies that mimic the final-energy use.

Other changes in these models are related to the inclusion of additional technologies for production of synthetic fuels and electricity generation. Given that Fischer-Tropsch (F-T) liquids (specifically F-T diesel) may have a promising potential as transportation fuels in the medium term, production of Fischer-Tropsch liquids (diesel) from coal and biomass has been included. Concerning the ERIS model, energy carrier production technologies for hydrogen production (from coal, gas and biomass), alcohol production (from gas and biomass) and petroleum production (from oil and coal) were also included, as well as an energy balance for each carrier. Moreover, transmission and distribution infrastructure for energy carriers were added to the model. The economies of scale in pipeline systems were also incorporated through specification of higher initial costs.

To better represent abatement options, a number of carbon capture technologies were added to both models. In ERIS, these capture technologies have been defined as add-ons to various emitting technologies and their costs (capital and operating) and energy requirements vary depending on the additional components required. ERIS allows capture of carbon from hydrogen and synthetic fuels production, conventional (steam) and advanced coal electricity generation, and gas combined cycle. Captured carbon is stored, with a user-defined percentage of total stored CO_2 assumed to leak each year. In GMM, Biomass gasification with and without CO_2 capture is now considered, in addition to biomass combustion power plants already existing in the model's database. CO_2 capture has been introduced for hydrogen production from coal and biomass gasification and steam reforming of natural gas, following several literature sources.

Marginal abatement curves (MACs) for the two main non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O), have been incorporated, considering both energy-related and non-energy-related sources. This approach uses the regional marginal abatement curves for non-CO_2 GHGs estimated by U.S EPA (2003). By incorporating MACs for these non-CO_2 GHGs, the context for the examination of energy-technology strategies in the GMM model is substantially improved.

The models have also been linked to the stylized climate model MAGICC version 4.1 (Wigley and Raper, 1997; Hulme et al., 2000; Wigley, 2003). MAGICC includes all the major greenhouse gases and the effects of rationalised (three world regions) fossil fuel-derived SO2 emissions through sulphate aerosol effects and allows the estimation of concentrations of greenhouse gases (CO_2, CH_4 and N_2O) in the atmosphere, global temperature change and average global sea-level rise. Thus, it allows the quantification of several key global indicators of climate change and the examination of the ability of alternative policy instruments to stimulate technological pathways that drive to a low-emissions energy system in the long run.

For the incorporation of the TFLCs in these models an iterative linear and MIP formulation has been applied (described in Turton and Barreto 2003). This involved iterating between the linear programming (LP) formulation of the models and an exogenous learning sub-module which incorporates the non-linear 2FLC formulations. Cumulative installations from the LP model form the input to the learning sub-module, which calculates new specific costs that are fed back to the LP model. The LP model is rerun with these new specific costs to determine new cumulative capacities, which are then processed by the learning module. The process is repeated until there is sufficient convergence. The specific costs at convergence are then applied to an MIP model that accounts for the non-linearities associated with transmission and distribution infrastructure development. The main drawback of this approach is that it eliminates foresight regarding the impact of learning on future technology costs. However, this loss of foresight regarding the effect of technology experience and R&D may in fact better reflect the uncertainty faced by decision makers when selecting the most suitable technologies (candidates for R&D). Moreover, from a technical standpoint, experiments with this formulation produce results almost identical to the equivalent MIP model, but solve considerably faster. This approach is not only well suited for incorporating the sophisticated learning formulation proposed for SAPIENTIA, but also facilitates more extensive examination of policy shocks. The MIP formulation is also well-suited for assessing the impact of an exogenous investment in deployment and demonstration (D&D) on a particular technology.

2.2.2. Extensions of the MARKAL-WEU Model

MARKAL is a bottom-up optimisation model operating under perfect foresight and covering Western Europe as a single region. The principal target of the MARKAL model analysis within the SAPIENTIA project has been to exploit its energy technology database for Western Europe to explore possibilities for additional technology spill-over within and across sectors. Once these relationships are established, the effects of learning-by-doing and learning-by-research can be analysed. It was not found possible to implement directly the TFLCs into the MARKAL source formulation so an approximate way has been used to incorporate them: the single factor learning rate is influenced by the R&D expenditures. By increasing R&D, a new (lower) learning rate is obtained which is then applied on the learning technology or component.

Work on the MARKAL model extensions has concentrated on the extension of the technology clusters for the 10 pre-SAPIENTIA key learning components, resulting in a broader cross sectoral spill-over. In total, 20 new key learning components have been added. These components are shared among a large number of technologies in the database and across different sectors. Important and promising key components are introduced in technologies in the buildings sector (residential and commercial and service buildings), fuel cells and in industry (boilers). The use of fuel cells in transport has been expanded to a larger number of automotive technologies. The inclusion of these non-power sector technologies in most cases doubles the number of technologies in which the key component can build up capacity (experience) and hence enables the reduction of the specific costs for future investments. This has resulted in a very large cluster matrix: combining the existing components with the extension and addition of the new ones, the total number of technologies affected by the 30 key components is well over 300: 354 in total of which 236 in the end users' sectors and 118 in the supply sectors.

The extensions being quite substantial, it should come as no surprise that problems concerning the solvability of the problem might occur. Retrieving an optimal solution is a challenging and time-consuming task for the existing mixed-integer solvers. To improve the performance of the problem solving, an alternative to the MARKAL paradigm cluster formulation was introduced. The new approach still allows for technology spillover as the key component is now modelled as a commodity that enters each technology in the cluster at the moment of investment in the technology. The amount of the commodity entering corresponds to the investment level on the technology. This approach shifts the bulk of calculation effort from the MIP solving to the LP (linear problem solving), gaining some speed in solution time. This results in better model performance, allows solutions at a lower tolerance level, and takes technology spillover into account; yet the approach is not sufficient to reach an optimal solution within acceptable running times, whereas the endogenous learning character of the technologies is lost, as the cost trajectory for the key components has to be estimated exogenously or has to be based on existing results from a previous ETL analysis.

2.2.3. Extensions of the POLES World Model

The POLES world energy model has been updated and considerably enhanced with a view to specifically serve the research needs of the SAPIENTIA project. A crucial task has entailed the extension of the time horizon of the detailed approach to energy technologies in the POLES model up to the longer term (2050). This has involved significant changes to the POLES modelling system, first because new technologies (not potentially significant for the medium term (2030) but much more important for the further future) had to be identified and introduced in the model and because the proper structure of the model had to be significantly modified. The most important developments in the model have concentrated on the description of the hydrogen economy, the development of decentralised electricity generation, the introduction of carbon capture and sequestration technologies for H_2 and electricity production and the integration of the Two Factor Learning Curves with clustering effects.

The modelling of the Hydrogen economy in POLES begins with the demand side. Hydrogen is supposed to be principally used through fuel cells, which have better efficiency than conventional engines either in stationary or in mobile uses. However, to avoid the exclusion of some possible niche market uses, thermal hydrogen vehicles are also considered as part of Hydrogen demand. For the very long-term analysis it was judged important to introduce a full treatment of competition among different distributed power generation technologies, including conventional cogeneration, Gas Fuel-Cells, Hydrogen Fuel-Cells and Solar building-integrated panels.

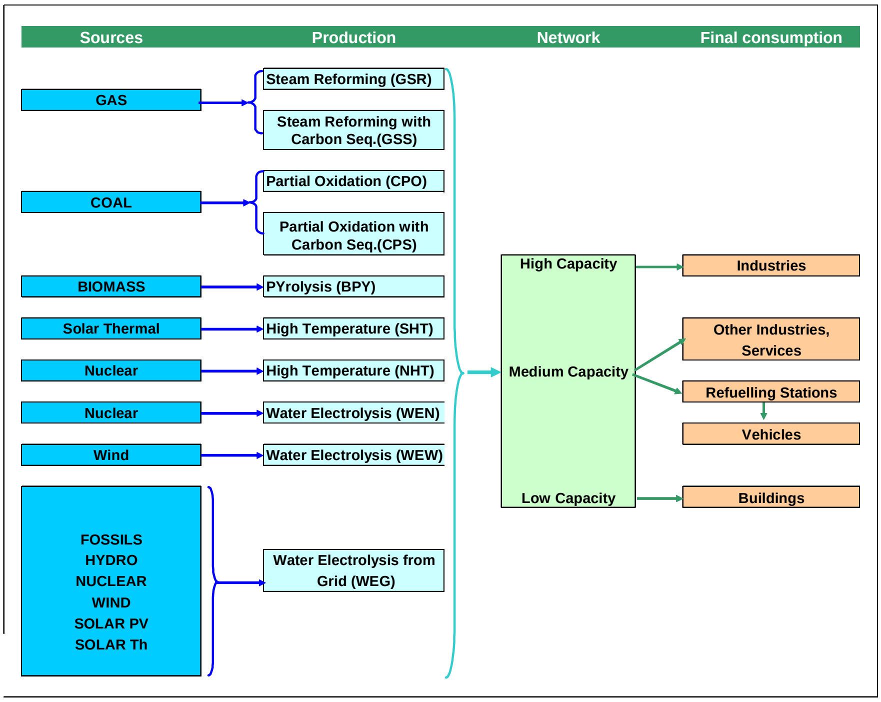
Regarding Hydrogen in mobile applications, in the new version of POLES two kinds of mobile fuel cell vehicles (one with hydrogen and one with methanol from natural gas) and one conventional hydrogen vehicle are taken into account[1].

In order to meet total Hydrogen demand, various options of hydrogen production have been identified. A large number of studies concerning hydrogen production have been scrutinised in order to choose the most representative and probable technologies to be included in the model. As a result, a set of key options (10 hydrogen production technologies) has been identified and the completion of the dataset characterising them has received utmost importance.

Due to Hydrogen's relatively low volumetric energy density, transportation and final delivery to the point of use is one of the most significant costs of the Hydrogen supply. For that reason the modelling framework has also taken into account in a detailed way the costs of transport infrastructures from the point of production to the point of use handling and moving within refuelling stations or stationary power facilities.

The resulting new hydrogen module in the POLES model is described in the following figure:

Figure 3: POLES Structure of the Hydrogen Module



In all, the simulation and modelling in POLES of hydrogen production and uses encompassed the following steps:

1. Total Hydrogen Production
2. Installed and available capacities for four categories of Hydrogen plants
3. Hydrogen production cost by plant category
4. Productions cost of the different plant categories and average full-costs for stationary and mobile demand

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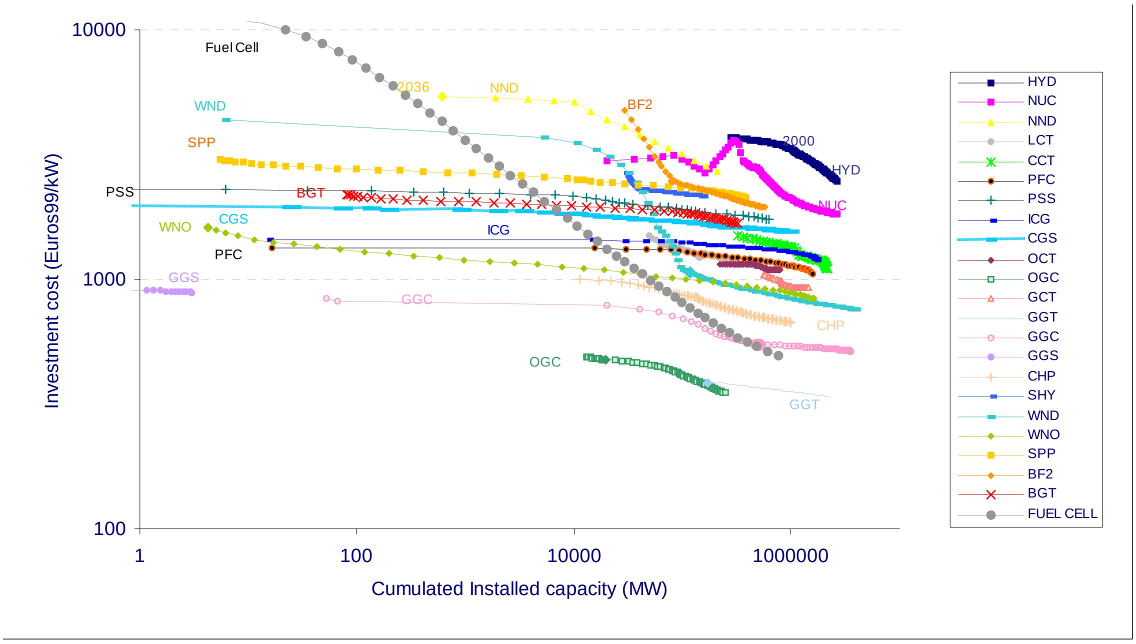
[1] The approach has been based on the extension of the transport module realised in the course of the WETO H_2 project.

5. Planning of new capacities (for following periods)
6. Transport and delivery costs

In POLES, Carbon capture and sequestration has been applied to three electricity generation technologies (Supercritical Coal, Integrated Coal Gasification, Gas turbine in combined cycle) and two hydrogen production technologies (Hydrogen from Gas Steam Reforming, Hydrogen from Coal Partial Oxidation). The modelling of carbon capture and sequestration encompasses the calculation of the capture and storage costs (cost of compression, transportation and injection), the calculation of the carbon stored for each country and in the world level and the calculation of the unit cost of the carbon stored.

The incorporation of technology dynamics in POLES has resulted in a set of complex and differentiated dynamics (see figure below).

Figure 4: POLES reference to 2050 with endogenous costs and TFLCs for electricity generation technologies[2]



Many technologies show a highly non-linear profile in a 50-70 years long-term perspective. Particularly, during the eighties and nineties, the dynamics of wind onshore technologies are consistent with the "technology shakeout" hypothesis.

In the case of the fuel-cells, significant learning is necessary to make this technology competitive with stationary and mobile conventional alternatives. In current simulations, the learning by doing and by searching effects are not sufficient to reduce the cost at the level that would be necessary to attain competitiveness compared with the conventional vehicles. In spite of the clustering effects, learning rates are generally lower than those observed for renewables in the last 20 years (shakeout).

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[2] Technology abbreviations are as follows: HYD: Large Hydro, NUC: Conventional Nuclear, NND: 4th generation nuclear, LCT: Lignite Conventional Thermal, CCT: Coal Conventional Thermal, PFC: Pulverised Supercritical Coal, PSS: Pulverised Supercritical with Sequestration, ICG: Integrated Coal Gasification, CGS: Integrated Coal Gasification plus Combined Cycle, OCT: Oil Conventional Thermal, OGC: Internal Combustion Engine, GCT: Gas Conventional Thermal, GGT: Gas Turbine, GGC: Gas Turbine Combined Cycle, GGS: Gas Turbine Combined Cycle with Sequestration, CHP: Cogeneration, SHY: Small Hydro, WND: Wind Onshore, WNO: Wind Offshore, SPP: Concentrating Solar Power, BF2: Biomass Combustion, BGT: Biomass Gasification

The results indicate that many secondary parameters and effects have to be taken into account for a full understanding of the learning rates (for example low load factors amplify the capacity increase, low lifetime amplifies the necessary cumulative production).

2.3. Extensions of the PROMETHEUS Stochastic Model

All models presented so far are essentially deterministic in character. The projections and variants produced using these models provide many interesting insights as to the future course of energy system variables. Such analysis offers a valuable means of exploring possibilities in a transparent and readily justifiable way particularly useful in supporting policy analysis. It does not however give any quantitative indication as to how likely some occurrences may be. Such information is often strategically important and could add a different dimension to the analysis performed. Stochastic models are appropriate tools for providing this type of information however very few of them exist covering energy systems.

ICCS/NTUA has developed PROMETHEUS, a tool capable of performing precisely this type of analysis. Originally conceived as a source of risk information for energy R&D portfolio exploration, PROMETHEUS covers, albeit in a more aggregate way (compared to the deterministic models) all the key aspects of the World energy system together with key global environmental issues (global temperature change). The model recognises three main sources of uncertainty:

- Uncertainty regarding assumptions and the evolution of exogenous variables
- Variation in variables that are not explicitly modelled since they are considered relatively unimportant but could cumulatively cause deviations (such deviations are usually assumed to be zero centred)
- Uncertainties arising from imperfect knowledge of the system and notably the parameters included in the model.

PROMETHEUS is a self-contained energy model consisting of a set of stochastic equations and identities (in total over 2100 equations). All exogenous variables, parameters and error terms in the model are stochastic and there is explicit representation of their distribution including terms of co-variance. As a result all endogenous variables are also stochastic. It also contains stochastic relations describing technology improvement dynamics (both learning by research and experience). The output from PROMETHEUS consists of a massive Monte-Carlo set representing at least 1000 alternative scenarios.

PROMETHEUS provides the probabilistic input necessary for giving the ISPA tool (the R&D policy exploration facility) its ‘hedging’ characteristics. Work on PROMETHEUS attempts to answer primarily two basic questions:

- How large are the uncertainties associated with the impacts of specific R&D actions on the different policy objectives
- How do these uncertainties impact on each other (i.e. does an overestimate of the possible impact of an R&D action on a target indicator imply an overestimate of the impact of another measure on the same or another indicator? Or on the contrary does it imply an underestimate?)

These are fundamental questions for policy exploration, especially in a field like R&D budgeting where uncertainties on the efficacy of actions can be very considerable due to the very nature of R&D which is effectively a speculative activity.

Work in SAPIENTIA has concentrated on the re-estimation and very substantial expansion of the PROMETHEUS stochastic model as developed in SAPIENT (which had limited the scope to power generating technologies). The ultimate aim has been to measure uncertainties arising from a great variety of sources: uncertainties on the various assumptions, errors on parameter estimates, errors arising from omitted factors.

A fundamental task undertaken within SAPIENTIA has been the extension of the model’s forecast horizon to the longer term (2050). To this end, work on PROMETHEUS has followed closely the specification of the longer term in POLES albeit in a less detailed fashion, especially with regard to regional and sectoral disaggregation. The extension to the 2050 time horizon has entailed significant changes in the PROMETHEUS modeling system with regard to the identification and introduction of new technologies and the modification of the structure of the model. Accordingly, PROMETHEUS has been extended to cover a more detailed transportation sector and to incorporate a Hydrogen Production, Storage and Delivery sub-model. In all, 22 additional technologies are represented in the new version (4 large scale power generation, 4 very low emission vehicles, one distributed power generation and 9 Hydrogen Production technologies).

The Hydrogen sub-module considers 9 technologies to compete on the supply side for the centralised production of H_2. On the demand side, hydrogen is introduced in the competitive market of distributed electricity production (through stationary fuel cells) and in the road transport sector (through fuel cell cars and the hydrogen internal combustion engine car).

The hydrogen and electricity systems are connected on the supply side through the electricity price in grid electrolysis and on the demand side through the competition between the decentralised fuel cell electricity production and the electricity from grid.

PROMETHEUS also incorporates competition between gaseous or liquid storage options and between pipelines and trucks for hydrogen delivery options.

Other important developments on the PROMETHEUS model include the endogenisation of climate policy (where climate change -as it is perceived to occur- affects the climate policy intensity) and the endogenisation of R&D, by making it dependent on energy costs, while renewable and CO_2 capture technologies shares in total R&D are affected by energy costs and the carbon value (climate policy intensity).

Finally, PROMETHEUS has been extended to incorporate technology dynamics for 51 technological options for electricity production, hydrogen production and passenger cars. These include:

- Capital costs parameters for 44 technological options
- Fixed O&M costs for 34 technologies; although they are basically labour costs, technical progress has been assumed based on the increased automation, reliability and the economies of scale
- Variable cost parameters for 7 technologies, adjusted for efficiency.
- Efficiency parameters for 20 technologies

3. Projections and Scenarios

3.1. Baseline Scenario

All models involved in the SAPIENTIA project have been used to build baseline projections in order to establish a benchmark against which the impact of R&D policies can be evaluated. This is an essential task as the extensive modelling activity undertaken within SAPIENTIA, altering in some cases drastically the coverage of the models in terms of sectors, technologies, time horizons and the addition of causality chains linking to Sustainable Development indicators has implied a substantial expansion of their output, which has to be monitored and validated by all modelling teams participating in the project.

3.1.1. Common Assumptions

The fact that all models are used to carry the R&D shock exercises requires that they share a modicum of common assumptions in order to avoid the emergence of spurious differences at the synthesis of experiments stage, where the input to ISPA is prepared. In recognition that the models have different sectoral, geographical and temporal coverage and that they are characterised by different philosophies (having been designed for different purposes) the assumptions harmonisation effort has been limited to some broad aggregates: demography, overall economic activity, climate policy intensity and R&D effort. The following paragraphs report on these common SAPIENTIA baseline assumptions.

World Population Trends

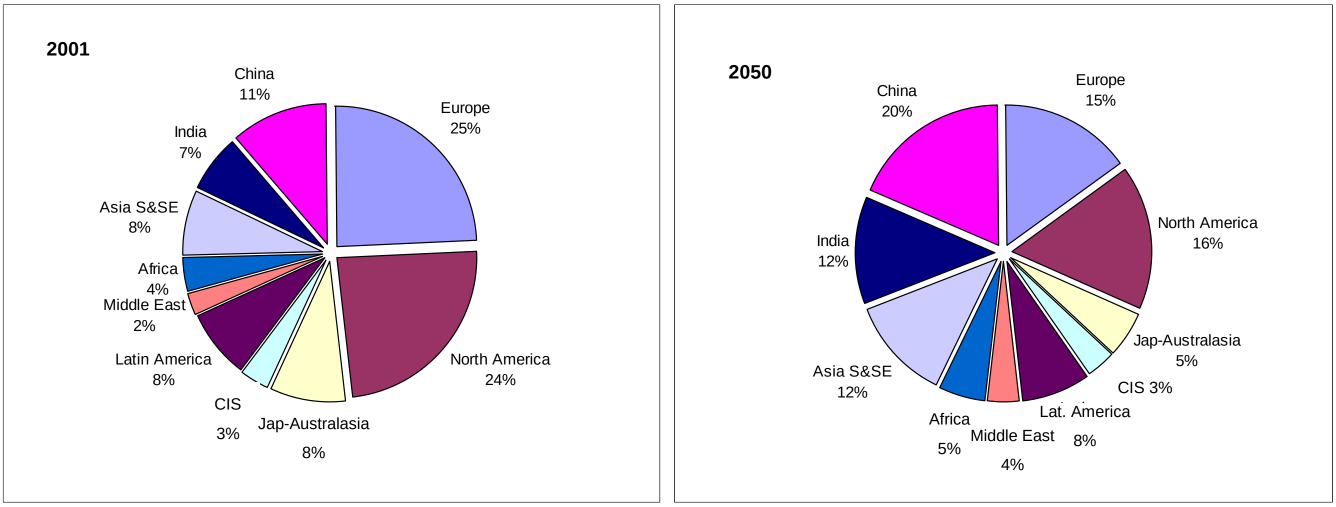
World population is expected to increase from little more than 6 billions today to 8.9 billions in 2050 with a marked decrease in average growth, which can be attributed to the demographic transition, whereas a stabilization in total population is expected in the second half of the century. By 2030 four countries or regions – India, China, Africa and Asia South & South-East (or Rest of Asia) –account for 1.4 billion each. In 2050 and on the basis of ongoing trends, Africa may be the most populated of the four regions with 1.8 billion.

Due to the ageing phenomenon, total population is expected to decrease in four world regions: Europe, Japan-Australasia, China (-0.2%/yr on average) and the Community of the Independent States (-0.5/yr on average). The Middle-East region and Africa show the highest growth rates over the period, with more than one percent per year increase between 2030 and 2050.

World GDP trend

World GDP is expected to grow steadily until 2050, although at a pace that progressively slows down, from 3.9%/yr in the current decade, to 2.9%/yr in the 2010-2030 period and 2.2 %/yr in the 2030-2050 period. Despite this slowdown, world output increases fourfold to 2050. The 2050 projection used in the SAPIENTIA study indicates a new geography of world production with four economic giants namely Europe, North America, China and India. Indeed, as presented in Figure 5 below, the outlook is dominated by the full emergence of Asia, the economy of which is expected to be multiplied by seven between today and 2050, despite a marked slowdown in its GDP growth after 2010. By the end of the projection, the four giants may constitute players of comparable size in the world economy, representing altogether two thirds of world product.

__Figure 5: World GDP structure, 2001 and 2050__



Climate Policy Assumptions

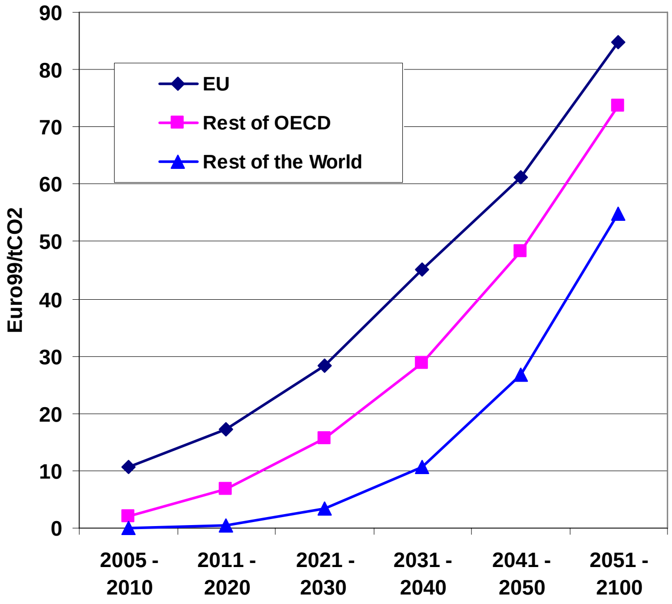
In the course of the specification of the SAPIENTIA Baseline scenario, the need for a reference case which would include some climate policy response was identified. This requirement arose primarily from reflection on the status of the baseline of PROMETHEUS: assuming no policy response in the Baseline would be equivalent to stating that there is no probability of such policy anywhere in the World for the next 50 years. Clearly such an assumption would alter drastically the nature of PROMETHEUS Baseline results from “maximum likelihood” to conditional distributions. Since the impact of R&D actions depends almost certainly on the presence of climate policies (encouraging some technological options while discouraging others) and in order to retain consistency within the integrated policy assessment process it was deemed necessary to perform the R&D sensitivity exercises within the context of some “median” climate policy stance.

Since no truly scientific expertise regarding the timing, extent, nature and probability of such policies is really available, it was decided to resort to a Delphi type methodology among partners in order to derive the essential input for this “with climate abatement policy” baseline scenario. The climate policy effort is measured through the introduction of an implicit carbon value (reflecting a carbon tax or the price of the permit in an emission quotas trading system).

The policy scenario assumes that the EU leads the world climate abatement effort, followed by lesser efforts in other industrialized regions. Developing regions undertake abatement efforts only after industrialized regions do and their efforts are smaller or equal to those in industrialized regions.

The resulting mean estimates for the carbon values in Europe, the rest of OECD countries and the Rest of the World, are illustrated in Figure 6 below. For Europe, the carbon value is regularly increasing, from 11 €/tCO_2 by 2010, to 45 €/tCO_2 between 2030-2040 and to 85 €/tCO_2 for the second half of the century (2050-2100). The other regions follow a similar path with a time-lag in the carbon value of slightly less than ten years for the Rest of OECD compared to Europe but of more than ten years for the Rest of the World compared to the Rest of OECD.

Figure 6: Carbon values in the world regions according to SAPIENTIA DELPHI

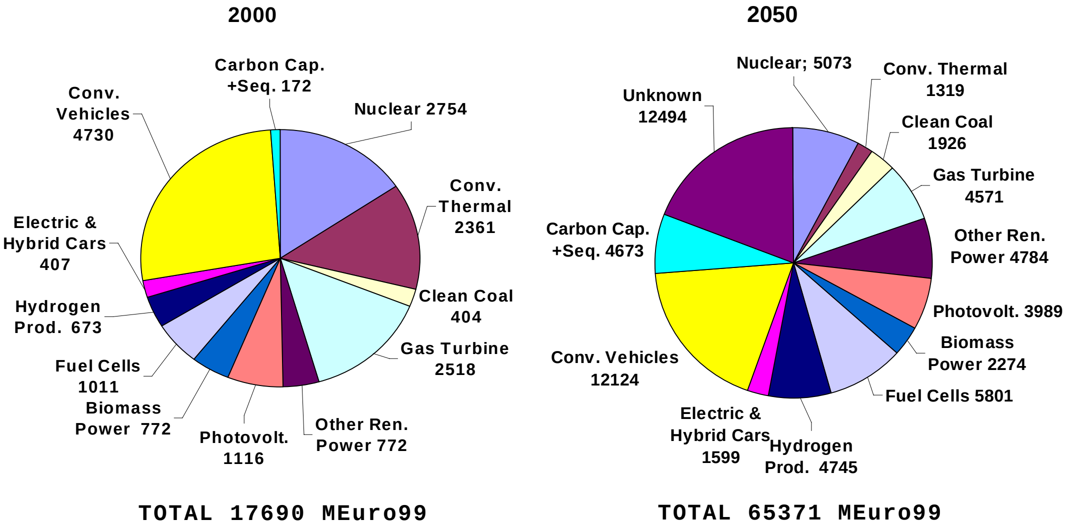


Public and Private R&D Outlook

All models participating in the SAPIENTIA project had to share the same or similar TFLCs. The use of Two Factor Learning Curves presupposes the availability of values for both capacity and R&D, either through model mechanisms or endogenously. Most models in SAPIENTIA generate values for capacity/technology take-up endogenously. Very few, however, include endogenous mechanisms for determining R&D expenditure on specific technologies. For this purpose, it was necessary to elaborate an outlook for R&D effort directed to different technological options, to be used as a common assumption for the construction of the reference cases of the different models. This Outlook is based on past trends, recent changes in emphasis and perspective analysis based on judgement, but does not intend to be the result of rigorous modeling logic. On the other hand, effort was devoted to maintain some consistency in order to allow a clear picture on a probable direction of future R&D to emerge.

The general shape of the outlook has been based on the neutral assumption that both Government Energy-related R&D (GERD) and Business Energy-related R&D (BERD) will grow proportionally with GDP, for the years following 2003. This assumption leads to a substantial growth in R&D on energy related technologies for the next 45 years and a reversal of trends apparent since the early eighties (broadly declining energy R&D shares in global GDP). Another crucial element of the R&D outlook derives from the assumption that an unknown technology attracting gradually but increasingly additional R&D expenditure will emerge from mid 2020's onwards. This assumption was made in order to avoid excessive concentration of R&D effort on a few technologies after support of more conventional technologies tapers-off. Apart from that, failure to include such an option would lack realism (there is bound to be unknown alternatives emerging in such a long period) and second would imply diminishing returns on future R&D effort which would in turn result in an overall R&D productivity and efficiency reduction.

Figure 7: Total Energy-related R&D in 2000 and 2050 (in MEuro)



The resulting distribution of the total (government and private) R&D budget between 13 technology categories (including the unknown technology) along the 2000-2050 period is presented above. It shows a first group of technologies which start from relatively high shares but experience a dramatic reduction of their weight in total R&D budget; these are nuclear technologies, conventional vehicle and thermal technologies. A second group is made up of technologies that begin with low shares and manage to retain them over time; these are clean coal and biomass power technologies, photovoltaics as well as electric and hybrid cars. Finally, the third group is made up of fuel cell, hydrogen and Carbon Capture and Sequestration technologies, which start as relatively marginal options in 2000 but show ever-increasing interest over time clearly evident in their 2050 shares.

3.1.2. Outlook using the POLES World Energy Model

ENERGY TRENDS

World primary energy consumption

The growth in world primary energy consumption is expected to progressively slow down, from 2.2 %/yr in the current decade, to 1.7 %/yr between 2010 and 2030 and 1.3 %/yr between 2030 and 2050. In spite of the slowdown, the level of total primary energy consumption more than doubles from current levels, reaching 22.3 Gtoe in 2050.

World primary supply by source

Despite rising constraints on CO_2 emissions in the presence of intensive climate change policies around the world, the projected significant use of carbon capture and storage technologies favours the emergence of coal as the key primary energy source at world level. Conversely, the dynamics of oil production and consumption are severely constrained by the growing scarcity of new reserves outside the Middle-East region, which translates in strongly increasing oil prices in the projection. Natural gas production is subject to supply constraints which become particularly evident shortly after 2040. Following 2010 nuclear energy production sees a fourfold increase by 2050.

The contribution of renewables to world supply in 2050 equals 3.52 Gtoe (slightly above the corresponding nuclear). Among renewables the dynamics are highly differentiated: supply from biomass initially slows down, but accelerates after 2020 when new biomass technologies develop; production from solar and particularly wind technologies increases sharply at more than 10 %/yr before 2030 and at 8 %/yr thereafter.

The long term oil production profile

The baseline projects high oil prices: 45 $/bl in 2020, 55$ in 2030, 85$ in 2050. These price levels strongly constrain oil demand. The peak in total conventional oil occurs between 2020 and 2030. Between 2040 and 2050 total oil production is stabilised with non conventional oil compensating for the continuous decline in non-Gulf production.

Due to the relative exhaustion of non-OPEC reserves, world oil production is expected to progressively concentrate in a limited number of countries. The ten largest oil producers – among which the only non-OPEC are Russia, the USA and Canada –represent almost 75 % of total world oil production in 2030 and 85 % in 2050. In 2050, non conventional oil represents 23 Gbl – i.e. the equivalent of the current Gulf production – almost equally divided among Tar Sands (Canada) and Extra Heavy Oil (Venezuela).

World gas production also peaks at around 2040, with the ten largest producers representing 80 % of total production after 2030. Among these ten largest, five play a key role with 70 % of total production, Russia, Saudi Arabia, Iran, Qatar and the US.

ENERGY TECHNOLOGY OUTLOOK

Power generation technologies

Over the first half of the century, electricity production broadly follows economic growth, with a first doubling of total generation between now and 2020 and a second doubling by 2050. Electricity from renewables quadruples, with wind energy (on and offshore) playing the most significant role, but also with a significant contribution of electricity from solar and biomass sources.

With regard to the relative weight of the different primary energy sources in the electricity fuel-mix the share of gas increases to 30% in 2020 but goes back to its current level of 20% in 2050; coal's share is between 30 to 40 % and the increases in nuclear and renewable (at more than 20% each) compensate for the extinction of oil in the power generation sector.

Hydrogen production

The POLES Baseline scenario is not particularly hydrogen intensive, as the total production of hydrogen-energy only reaches 200 Mtoe in 2050, a figure only slightly superior to the current production of hydrogen-feedstock. The 2050 production mix is dominated by hydrogen production from biomass pyrolysis, followed by electrolysis in dedicated nuclear power plants and hydrogen from fossil fuels, with a relatively balanced contribution from coal and gas, with and without CO_2 capture and Storage at the final years of the period.

Carbon Capture and Sequestration

The development of CO_2 Capture and Storage begins after 2020 and increases rapidly thereafter. From the 48 000 TWh produced by thermal power plants in 2050, almost one fourth is produced with a CCS facility. Annual storage reaches 8 $GtCO_2$ in 2050, i.e. about one third the current total CO_2 emission level. Total cumulative CCS in 2050 corresponds to 90 $GtCO_2$ i.e. four times the current annual emissions. In the POLES baseline, CCS is far from a marginal option in the world energy system.

SUSTAINABLE DEVELOPMENT

World CO_2 emissions

Total net CO_2 emissions from the energy sector are stabilised beyond 2040. This pattern is attributed to a host of factors: high primary energy prices and the introduction of a carbon value restrict total energy demand whereas emissions are further reduced by the increased contribution of non fossil fuels (renewables and nuclear) and finally by the increasing application of CCS technologies, the contribution of which brings down the 2050 gross annual emissions from 50 $GtCO_2$ to 42 $GtCO_2$.

High energy prices, structural factors and high carbon values operate to stabilise emissions in the Annex I region by 2020; a decrease in emissions is projected thereafter. By 2050 Annex 1 emission levels are lower than today; consequently all incremental CO_2 emissions originate from non-Annex 1 regions.

World oil resources

POLES allows for a dynamic treatment of the oil discovery process (endogenous process) whereas resource hypotheses are exogenous[3]. While more than 900 Gbl of oil have been produced today, identified reserves correspond to 1 100 Gbl and recoverable but yet to be identified resources may add 600 Gbl. Total recoverable oil is thus estimated to 2 600 Gbl, including past production. Of the 1 700 Gbl of oil that remains to be produced 800 come from the Gulf region and more than 200 from the other OPEC countries, which allows to insist on the strategic aspects of oil activities in those regions.

However, the dynamic treatment of technological progress on the Recoverable resources (as implemented in POLES) indicates that recovery rates increase the total recoverable oil resources from 2 600 Gbl today to 3 300 Gbl in 2050.

World gas resources

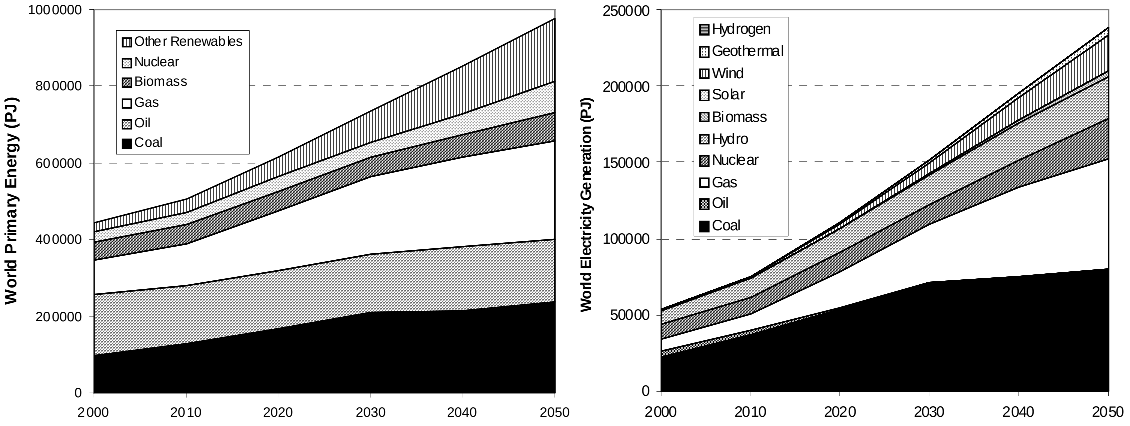
A very similar approach is used for the natural gas discovery and development process in the key gas producing countries. The results indicate that the gain in Recoverable Resources due to technological progress is limited in the case of natural gas. However, at the beginning of the simulation the ratio of cumulative production to Recoverable Resources is lower, i.e. 18 % only for gas against 32 % for oil, indicating that up to now gas resources have been less exploited than those of oil.

3.1.3. Outlook using the GMM Model

ENERGY TRENDS

The figure on the left below presents the world primary energy consumption in the baseline scenario. By 2050 world primary energy consumption more than doubles compared to 2000 levels, reaching about 950 EJ. Fossil fuels dominate the primary energy mix during the first half of the 21st century. The use of natural gas, the less carbon-intensive fossil fuel increases significantly. Coal consumption also grows in absolute terms but to a lower extent while oil consumption grows slightly. The growth of coal consumption is basically driven by the use of coal for electricity generation. Nuclear energy experiences a revival and its contribution grows significantly.

Figure 8: World primary energy consumption (left) and World electricity generation by fuel (right) in the GMM baseline scenario between the years 2000 and 2050.



The figure on the right above presents the global electricity generation mix by fuel in the GMM Baseline. Global electricity generation sees a fourfold increase in the period 2000-2050. Coal-based power plant production grows fast until 2030 but decelerates thereafter. A gradual transition occurs from conventional coal-fired plants towards more efficient and clean coal plants. Renewable, nuclear and gas-fuelled generation contribute substantially to total generation over the projection period. Among new renewables, wind and to a lower extent, biomass generation make significant inroads into the system. By 2050, wind power generation (onshore and offshore) accounts for half the total renewable electricity generation. In the case of biomass, combustion-based facilities are gradually replaced by more efficient and flexible biomass gasification systems, accelerating its growth.

TECHNOLOGY OUTLOOK

Transport Sector

According to the GMM Baseline a technology transition takes place in the global passenger car sector. While conventional internal combustion engine vehicles dominate the passenger car mix during a large part of the first half of the 21st century, their market participation declines gradually towards 2050. Advanced ICE vehicles and hybrid-electric vehicles gradually, but steadily, gain market share. Specifically, natural gas-powered and oil-product-based hybrid-electric vehicles grow fast accounting together for about 20% of passenger car mobility in the year 2050. Electric vehicles occupy a niche market while fuel-cell hybrid vehicles remain “locked-out” and do not penetrate the market during the first half of the century.

SUSTAINABLE DEVELOPMENT

Greenhouse Gas Emissions/Concentrations

Despite the influence of increasingly binding climate-change policies around the world, global CO_2 emissions still grow but with a diminishing growth rate. By the middle of the 21st century, CO_2 emissions are approximately 11.5 Gigatons of carbon, which represents more than 80% increase relative to 2000 levels. The bulk of emissions growth comes from developing regions and, specifically, developing Asia. CO_2 emissions in currently industrialized regions -where the highest carbon values are imposed- decline in the long term.

Aggregate emissions of the three greenhouse gases included in the analysis (CO_2, CH_4, N_2O) reach approximately 17 Gton of C-eq in 2050. CO_2 emissions[4] represent the largest fraction, followed by CH_4 and N_2O. Cumulative CO_2 emissions and cumulative CH_4 emissions for the period 2000-2050 equal 557 Gt C-eq. and 188 Gt C-eq respectively.

Atmospheric CO_2 concentrations reach approximately 479 parts per million in volume (ppmv) in the year 2050. CH_4 concentrations in 2050 are about 3200 ppbv, whereas N_2O atmospheric concentration is much lower in the year 2050 (373 ppbv).

Temperature Change – Sea Level Rise

Global temperature change relative to 1990 reaches about 1.5^{o}C in 2050 with a “commitment” of approximately 1.9^{o}C for the year 2065 (15-year commitment, on the assumption that GHG emissions after 2050 remain constant at 2050-levels). Sea-level rises by 16.5 cm in 2050 and by a “commitment” of about 22.5cm for 2100.

Regarding the global temperature increase per decade, the decadal rate of variation of temperature increases over the 2000-2050 period, attaining values above the “safe” 0.20oC/decade discussed in the literature. The highest temperature increase over a decade occurs between the years 2040 and 2050 and equals to 0.29^{o}C.

World Oil and Gas Reserves

By the middle of the 21st century, at world level, the oil Resources to Production ratio equals to 75 years while the natural gas Resources to Production ratio is approximately 89 years.

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[4] Only energy-related CO_2 emissions are considered here

3.1.4. Global Outlook beyond 2050 using the ERIS model

Due to the long term dynamics of technical change and R&D actions, the full effect of a given strategy for achieving desired sustainability outcomes is brought to bear only over many decades. It is therefore useful to put the analysis also into the context of a longer-term study. Such a context can give an indication of possible plausible continuations of the medium-term (2050) policies and thereby an idea of their longer-term (2100) impacts.

ENERGY TRENDS

The most noticeable transition across the century is the declining share of fossil fuels in electricity generation which is not surprising, considering the imposition of GHG taxes assumed in this scenario. In **absolute** terms however, generation from both coal and natural gas increases until the third quarter of the century, and generation from gas fuel cells is still increasing in 2100. The decline in aggregate generation from fossil fuels coincides with an increase in generation from nuclear (both 3rd and 4th generation) and renewable sources of energy. If we look across the whole century, the dominant sources of global generation shift from: conventional coal, nuclear and hydroelectric generation in 2000, to gas combined cycle, conventional coal and nuclear in 2050, and finally to conventional and advanced nuclear, and hydrogen fuel cell generation in 2100.

The continuing dominance of fossil fuels mid-way through the 21st century, even under a baseline scenario that includes climate change mitigation policies, illustrates the inertia of energy systems, particularly the time taken for new technologies to become competitive and penetrate the market on a large scale.

TECHNOLOGY OUTLOOK

Oil refining continues to play a dominant role throughout much of the century, and total combined output of other fuels from new energy production technologies (such as hydrogen synthesis technologies based on steam reforming of natural gas, pyrolysis of biomass and partial oxidation of coal) only surpasses petroleum output after 2080. Penetration and uptake of biomass- and coal-based hydrogen synthesis technologies is faster in the second half of the century, and total hydrogen output in 2100 is roughly equivalent to refinery throughput in 2000. The fact that hydrogen production from coal partial oxidation is supported may initially seem surprising when one considers the impact of a GHG tax, but occurs nonetheless because it represents a more efficient way of utilising the energy in coal where the resulting hydrogen is used in a fuel cell, and more importantly, is amenable to carbon capture.

In the transportation sector, the gradual transition away from the conventional petroleum ICE vehicles to natural gas-fuelled vehicles (both conventional ICE and hybrid electric ICE) projected for the first half of the century leads to the displacement of the gasoline ICE vehicle as the dominant transport technology, and its replacement by the gas hybrid between 2040 and 2060. Hybrids continue to play a dominant role in the transport market for the remainder of the century, although the cost premium of the technology renders it unable to achieve a market share of much more than 60 percent. The increasing availability of zero-emissions alcohol fuel in the second half of the 21st century results in the gradual penetration of this fuel into both the hybrid and conventional ICE market, and the availability of relatively cheap natural gas in some world regions also ensures that the conventional ICE technology maintains a significant market share, even though gasoline plays almost no role by 2100.

Carbon capture and storage (CCS) technologies continue to penetrate the market, and by 2100 around 2.0 Gt of carbon are captured annually (which is close to 14 percent of energy-related CO_2 emissions). Over 80 percent of this carbon is captured from advanced coal plants, and in hydrogen and synthetic fuel production, with technologies that capture carbon from post-combustion flue gases remaining relatively unattractive despite the climate change mitigation policies assumed under this baseline scenario.

Nuclear technology remains relatively expensive compared to other forms of power generation yet plays a major role in the electricity market at the end of the century because of depletion of gas resources, and the impact of the GHG tax on the competitiveness of coal-fired generation. This is also the case with most renewables, with the share of wind turbines limited by the availability of suitable sites.

Clearly, by the end of the 21st century fuel cells are the cheapest form of electricity generation capacity. However, the challenges associated with mobilising resources for hydrogen production, and developing the necessary distribution infrastructure constrain the penetration of this technology. This suggests the fact that in order to fully exploit the potential of fuel cell technologies, the key may be to develop a long-term strategy for development and investment to co-ordinate hydrogen production, distribution and utilisation.

SUSTAINABLE DEVELOPMENT

Global net greenhouse gas emissions continue rising until around 2070 where they peak at almost 22 Gt carbon equivalent per annum. Apart from a shift to less carbon-intensive energy sources one of the main sources of abatement comes from sequestration – both geological and terrestrial.

Atmospheric concentrations of carbon dioxide increase from around 350 ppmv in 2000 to around 700 ppmv in 2100. By the end of the century average global temperature increases to around 3.2 oC above 1990 levels, while the average sea level rise equals to more than 400 mm.

3.1.5. Stochastic Outlook using PROMETHEUS

The main aim of the PROMETHEUS stochastic outlook is to:

- Provide assessments on the likelihood of key assumptions underpinning the Baseline. Such assessments provide insights on their status (for example the relative “optimism” or “pessimism” that characterises them). Such assessments can also take the form of joint probability analysis as for example an evaluation that a particularly favourable outcome occurs at the same time as another also favourable outcome.

- Provide assessments on ranges of key results thus giving indications as to the uncertainty associated with them. Unlike most ranges routinely reported in forecasting exercises PROMETHEUS assessments are characterised by a certain degree of rigour as they will have specific probabilities associated with them (quantiles).

ENERGY OUTLOOK

International Fuel Prices

The PROMETHEUS baseline projects high oil and gas price means in 2050; 84€00/bl for oil and 554€00/toe for gas. PROMETHEUS results indicate that there are significant probabilities to observe international fossil fuel prices that are higher than today’s levels. In 2050 the probability that the oil price will exceed 100€00/bl is 27.6% and the probability that the oil price will be less than it is today (the average oil price in 2005 is estimated at 45€00/bl) is 15.1%. The probability that in 2050 the gas price will exceed 735€00/toe is 21.6%; the probability to be lower than it is today (the average gas price in 2005 is estimated at 203€00/toe) is 5%. The probability that the coal price will be higher than 70€00/tn is 21.9%, whereas the probability that coal price will be lower than it is today (around 32.8€00/tn) is 19%. Finally, the probability that the gas price will be more expensive than oil in 2050 is 38%.

The above results indicate that there are significant probabilities to observe international fossil fuel prices that are considerably higher than the levels of today. Gas is expected to be an expensive fuel in the future and there is a considerable probability to be more expensive than oil.

Primary Consumption

At the global level, the average annual growth rate of total primary consumption is expected to gradually slow down in the next 50 years. The historical (1971-2000) observed average annual growth rate for the period 1971-2000 (equal to 2.1%) has 30% probability to be exceeded in the period 2000-2030.

Despite rising carbon values, coal consumption is expected to increase faster than oil and gas. This occurs in all regions except Europe, where the carbon values are on average high enough to prevent it. Natural gas is less affected from carbon values in the first 30 years. But progressively gas is turned into an expensive energy form due to increasing scarcity resulting in higher prices, which leads to gradual decreases in consumption beyond 2030. In sharp contrast to the rapid increase in coal, oil consumption decreases in the developed countries, due to higher oil prices.

TECHNOLOGY OUTLOOK

Transport Sector

Hybrid cars have the highest probability to be the cheapest option in 2050 for the European consumer (69.8%), followed by diesel cars (21.7%) and H_2 internal combustion engine cars (2.4%). The probability that hybrid cars will be cheaper than conventional gasoline cars in terms of cost per km is more than 92%. Fuel cells have only 1.2% (hydrogen fuel cells) and 0.8% (gas fuel cells) probabilities to be cheaper than conventional gasoline cars in 2050. Hydrogen fuel cells have 97% probability to be cheaper than gas fuel cells in 2050. In general, gas fuel cells can not be considered as a long term option, but only as short term alternative until hydrogen fuel cells dominate the market. The same applies to the H_2 internal combustion engine car which appears to represent a stop gap solution, before fuel cells become sufficiently attractive after 2030.

Fuel cells have high risks and high prospects. They can completely be out of the market or fully dominate it (minimum 0%, maximum 93% of new registrations in Europe in 2050). According to PROMETHEUS results, the penetration of fuel cells in the transport market is constrained by the high cost of the fuel cell stack itself and not by the cost of hydrogen. The above results suggest that the penetration of hydrogen in transport depends mainly on the penetration of the fuel cells and not on the penetration of the H_2 internal combustion engine car.

Regarding the global share of non conventional cars in the total passenger car stock in 2050 the probability to have more non-conventional than conventional cars in 2050 is 46.5%; the probability for their share to be less than 15% or higher than 85% is 5%.

Power Generation Sector

Currently, the Gas Turbine Combined Cycle technology, through its low cost, high efficiency and flexibility of use, represents the most attractive option for new generation plants. By 2050 this situation is projected to be radically altered. As regards electricity generation costs, Wind offshore has the highest probability (98.4%) to be cheaper than Gas Turbine Combined Cycle, followed by New Nuclear (98.1%), Biomass Gasification (97.2%) and Coal Gasification (80.2%).

Looking at the corresponding figures for 2025 the results indicate that the current dominance of the Gas Turbine Combined Cycle is unlikely to extend beyond the medium term when the likelihood of high gas prices increases and many competing options have a good chance of becoming economically attractive.

Share of selected technologies in electricity production in 2030 and 2050 in Europe

The share of renewable electricity production is expected to be close to the share of nuclear electricity production (in 2030 the means are 17% and 21% respectively, while in 2050 renewable electricity has a slightly higher mean than nuclear electricity - 24.4% and 22.6%). Among the renewable technologies the probability that wind will have the highest share in 2050 is 61.5%. The probability that wind offshore production will be bigger than wind onshore in 2050 is 30% (in 2030 it is only 3%). This result suggests that wind offshore will not come into the electricity production until the combination of the following occurs: wind onshore cost reduction, effective climate policy and high gas prices.

The CO_2 capture technologies benefit only in situations where high carbon values are introduced. The high uncertainty surrounding CO_2 capture technologies is stemming from the uncertainty surrounding an effective climate policy.

Nuclear electricity production is surrounded by considerable uncertainty. In the medium term there is only a 10% probability that the nuclear share will be higher in 2030 than in 2000, which reflects the current prospects for restricting nuclear expansion in Europe and the United States. However, in the longer term, where intensive climate policies are likely to occur in combination with high fossil fuel prices, the probability that nuclear increases its share in 2050 from 2000 levels is 17.8%.

Hydrogen Sector

The PROMETHEUS baseline scenario does not incorporate on average major and worldwide policy initiatives to favour hydrogen as a fuel. The expected hydrogen demand in 2050 is 120Mtoe with a standard deviation of 161Mtoe at the global level. This reflects the high uncertainty in the penetration of hydrogen in demand sectors, which results from high uncertainty concerning the ultimate reduction in the cost of fuel cells.

Hydrogen is more likely to be produced by renewable and nuclear technologies. Electrolysis (nuclear, wind and directly from the grid) does not appear as a likely option for large scale production. On the other hand the analysis suggests keen competition between renewable and fossil fuel technologies (the likelihood of the one or the other prevailing depending to a large extent on carbon value uncertainty) and between nuclear and renewable technologies (dominated by uncertainty concerning breakthroughs on nuclear or alternatively a more decentralised power generation structure).

SUSTAINABLE DEVELOPMENT

CO_2 Emissions

Regarding energy related CO_2 emissions, the probability to exceed the historical (1971-2000) average annual growth rate is 0.1% in Europe (historical: 1.1), 5.3% in the Rest of OECD countries (historical: 1.4) and 81.4% in LDCs (historical: 2.3). At the global level, the probability to exceed the historical average annual growth rate is 63.3% (historical: 1.7) reflecting the projected dominance of LDCs in global emissions. In the developed world the probability of actually observing a reduction in CO_2 emissions over the whole horizon is around 75%. On the other hand for LDCs the probability of such an occurrence is virtually non-existent.

Temperature Change

The mean projected temperature change in 2065 from 2000 levels[5] is +1.02oC and the standard deviation is 0.36oC. The probability of a temperature increase of more than 2oC from pre-industrial levels is 22.1% whereas the probability to observe an increase of more than 0.2oC is 91%. There is a 40% probability that the decade where the maximum increase in temperature occurs will end between 2040 and 2050. On the other hand there is still a 14.3% probability that it may end before 2020.

World Oil and Gas Reserves and Supply

In 2001 the conventional oil Reserves to Production ratio was 47 years up from 21.9 in 1979. According to PROMETHEUS results the probability of exceeding the 1979 figure in 2050 is 95%, while the probability of exceeding the 2001 value is only 8.7%. Gas Reserves to Production ratios have been more or less steadily increasing in the last 30 years from around 35 to around 78 years. The probability of exceeding present gas Reserves to Production ratios in 2050 is only 5.2%.

Security of Supply

The measure of security of supply is the maximum increase in oil and gas price average in any 3-year period of the forecasting horizon. According to PROMETHEUS results, there is a 74% probability that the maximum oil and gas average price in any 3-year period in the next 50 years will be higher than the price increase observed in the oil crisis period 1978-81 (Iranian revolution and Iran-Iraq war); the price increase in that period was around 150€00/toe.

GENERAL REMARKS ON PROMETHEUS STOCHASTIC OUTLOOK

Table 2 gives correlation coefficients between some key/indicative variables of the outlook. The first column of the table reveals a key feature of the outlook: PROMETHEUS results suggest that uncertainty concerning the future energy system lies mostly along an axis dominated by economic activity.

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[5] PROMETHEUS considers a 15 years commitment period in temperature change, thus in order to observe the temperature change due to 2050 greenhouse gases concentrations the climate module is run forward to 2065

Table 2:Correlation matrix of a subset of PROMETHEUS variables denoting the dominance of the economic activity; Bold figures mark correlations greater than 0.4; red highlights significant negative correlations

	World GDP av. annual growth rate	Av. oil int. price	Av. gas int. price	Av. carbon value	Cum. CO2 emiss.	Elec. final cons. in 2050	Other final cons. in 2050	Transp. activity in 2050	REN share in elec. prod. in 2050	H2 dem. in 2050	Non conv. Veh. share in 2050	Non conv. oil prod. in 2050	Cum. R&D in 2050	Biomass gassif. capital cost in 2050	Integr. Coal Gasif. capital cost in 2050	De-central. PV capital cost in 2050
Average oil int. price	**0.58**															
Average gas int. price	**0.47**	**0.75**														
Average effective carbon value	0.07	0.04	0.04													
Cumulative CO2 emissions	**0.54**	**0.41**	0.27	-0.12												
Electricity final consumption in 2050	**0.77**	**0.47**	**0.42**	0.00	**0.57**											
Other final consumption in 2050	**0.60**	**0.45**	0.35	-0.22	**0.45**	**0.43**										
Transport activity in 2050	**0.59**	0.30	0.21	-0.15	0.37	**0.46**	**0.40**									
Renewable share in elec. prod in 2050	0.08	0.12	0.21	0.13	-0.02	0.02	0.04	0.00								
Hydrogen demand in 2050	0.29	0.20	0.26	0.07	0.17	0.25	0.23	0.19	0.01							
Non conventional vehicles share in 2050	0.15	-0.11	-0.01	-0.01	0.05	0.16	0.10	0.19	-0.04	0.27						
Non conventional oil production in 2050	**0.44**	**0.77**	**0.51**	0.03	0.32	0.36	0.34	0.19	0.03	0.15	-0.10					
Cumulative R&D expenditure in 2050	**0.75**	**0.82**	**0.80**	0.17	0.34	**0.59**	**0.48**	0.39	0.18	0.30	0.03	**0.61**				
Biomass gassification capital cost in 2050	**-0.74**	**-0.83**	**-0.84**	-0.18	-0.35	**-0.60**	**-0.46**	-0.38	-0.21	-0.28	0.01	**-0.59**	**-0.96**			
Integrated Coal Gasificiation capital cost in 2050	**-0.65**	**-0.67**	**-0.64**	-0.04	**-0.45**	**-0.56**	-0.39	-0.35	-0.07	-0.26	-0.04	**-0.47**	**-0.75**	**0.78**		
Decentralised PV capital cost in 2050	**-0.45**	**-0.48**	**-0.53**	-0.11	-0.22	-0.35	-0.30	-0.25	-0.18	-0.19	-0.02	-0.31	**-0.58**	**0.61**	**0.48**	
New nuclear capital cost in 2050	**-0.40**	-0.35	-0.37	-0.07	-0.17	-0.38	-0.22	-0.22	0.10	-0.10	-0.05	-0.26	**-0.44**	**0.45**	0.31	0.29

High growth in world economic activity is associated with:

- Fast fossil fuel resource depletion resulting in slower reserves addition, tighter fuel supply, and ultimately high or even very high international fuel prices.
- Higher emissions of CO_2 and other GHGs leading to high concentrations and increasing the risk of damaging climate change.
- High R&D investments both because of the higher availability of funds generated from the higher activity levels but also as a result of the urgency created by the higher fossil fuel prices.
- Extensive technological innovation arising both from learning from research but also through the accumulation of experience as the capital stock is turned over faster, new technologies replacing more traditional one.

The combination of the last two points implies a higher likelihood of low capital costs and high variable costs for energy transformation and use, which lead to increased capital intensity and radical change in the energy system. Clearly, the opposite picture is more likely to emerge in cases of lower growth giving lower prices and emissions, weaker R&D investments, less innovation and a more static energy system.

A major conclusion from the above is that uncertainty is driven by demand in a resource constrained world where both demand and supply are relatively price inelastic.

This has important implications for strategies aimed at increased sustainability, especially with regard to environmental damage. There seems to be little likelihood of some of the "virtuous cycle" scenarios that seem to be so popular in perspective analysis. Such scenarios usually describe a rapidly changing energy system both in terms of technological innovation and economic and social structure combined with improved environmental performance but without involving lower economic activity and resource restrictions thus maintaining a reasonable cost of energy services. The major policy challenge is to define a strategy that raises the likelihood of such occurrences from the presently very low levels.

3.2. R&D Policy Scenarios

One of the most fundamental issues addressed within the SAPIENTIA project has been the importance of R&D (and in particular public R&D) in influencing the energy system towards sustainability. To explore this issue, two alternative scenarios of future R&D support have been developed: a “High R&D Scenario”, implying the doubling of total energy-related R&D (Government and Private for the whole world) on the technologies covered within SAPIENTIA over the period 2006-2025, and a “Zero GERD” scenario, implying the elimination of Government energy-related R&D (GERD) worldwide from the whole Outlook (to 2050).

The two scenarios have been constructed to represent changes in R&D of a similar magnitude. The structure of government and total energy related R&D budget has to some extent influenced the outcome of these two scenarios. The public R&D budget outlook is dominated by conventional and advanced nuclear power research, which amounts to slightly above half the total Government R&D funding. Renewable energy technologies attract 15% of the budget, almost half of which is directed to Photovoltaics. Clean coal technologies obtain over 7 percent, whereas Fuel Cells and non-conventional vehicles attract around 4 percent each. On the other hand, the Private R&D allocation is dominated by conventional vehicle technologies, which absorb over one third of the budget. Renewables account for over 15 percent, while Fuel Cells figure with a larger share relative to public R&D allocation (6%). Nuclear power is restricted to low shares in private research funding (4%), whereas non-conventional vehicles and clean coal technologies attract limited shares (1.8 and 1 percent respectively).

3.2.1. Impact of Scenarios on Technology Performance

Although the models used were different in their structures and coverage (simulation, perfect foresight, stochastic, long-term, medium-term), a broad consensus on the technological impact of the scenarios emerges.

Table 3: Impacts on learning and competition between technologies (examples from POLES and PROMETHEUS)

	Investment Cost (% Change from Baseline in 2050)				Capacities (% Change from Baseline in 2050)			
	High R&D		Zero GERD		High R&D		Zero GERD	
	POLES	PROMETHEUS	POLES	PROMETHEUS	POLES	PROMETHEUS	POLES	PROMETHEUS
Coal Conventional Thermal	-0.2	-0.2	*0.1*	*0.0*	-4.2	-6.1	*2.7*	*10.9*
Supercritical Pulverised Coal	-1.8	-1.8	*8.4*	*8.8*	-6.0	-4.1	*-1.9*	*-5.5*
Pressurized Supercritical with Sequestration	-1.2	-1.8	*5.5*	*8.5*	-10.9	-0.7	*-0.1*	*-1.0*
Nuclear (2nd and 3d gen.)	-0.7	-2.5	*2.1*	*5.8*	-9.8	-5.7	*3.2*	*6.0*
New Nuclear (4th gen.)	-19.0	-12.0	*84*	*124*	27.1	47.3	*-67*	*-85*
Wind Turbines Onshore	-2.1	-2.4	*3.7*	*2.9*	0.0	-3.7	*-1.8*	*10.7*
Solar Thermal Power Plant	-3.2	-3.1	*13.2*	*12.2*	1.0	1.6	*-7.2*	*-24.4*
Building Integrated PV	-3.9	-6.4	*6.8*	*5.6*	8.7	35.6	*-9.8*	*-6.1*

Fourth generation nuclear power appears to be the broad option that is most sensitive to R&D funding. In the zero GERD scenario most models indicate double costs in 2050 for this technology and possible failure to penetrate the market. On the other hand, in the High R&D case it ends up with a capacity that is considerably (27 to nearly 50 percent) higher than the reference case. These effects are dominant and affect many other technological options (including clean coal, conventional nuclear and some renewable options) that experience crowding out effects, though their costs and efficiencies do improve. The demise of fourth generation nuclear in the

Government R&D elimination scenario favours a number of technological options (conventional coal and some gas-based technologies), but most notably conventional nuclear, which registers considerable gains in capacity (3 to 6 percent increase according to most models) despite receiving lower funding.

New coal technologies – with and without Carbon Capture and Sequestration–display an intermediary profile, as they register higher costs and lower capacities in the public R&D elimination case, but do not benefit from the substantially increased R&D funding in the "High R&D" case, as their diffusion is lower in the latter case than in the reference. This can be interpreted as a consequence of "cluster effects": these new technologies are dependent on the development of conventional technologies that suffer from increased competition in the "High R&D" case.

Table 4: Impact of scenarios on non conventional vehicles and Fuel Cells (source PROMETHEUS)

	% share in total stock (2050)									**% change from Baseline (2050)**	
	Europe			**Rest of OECD**			**Rest of the World**			**Engine Cost**	
	Baseline	**Zero GERD**	**High R&D**	**Baseline**	**Zero GERD**	**High R&D**	**Baseline**	**Zero GERD**	**High R&D**	**Zero GERD**	**High R&D**
Fuel Cell Vehicle	5.0	2.4	19.0	4.6	2.1	17.1	4.4	2.0	16.6	*46.4*	*-38.0*
H2 Internal Combustion Engine	8.2	8.8	6.5	7.0	7.4	5.7	4.2	4.4	3.4	*-0.3*	*1.0*
Hybrid Vehicle	36.8	36.3	33.0	36.4	35.9	33.1	32.3	32.0	29.5	*0.9*	*-1.4*
Electric Vehicle	5.7	5.4	5.3	3.6	3.4	3.5	6.1	5.7	5.8	*1.7*	*-1.0*
Total non conventional	55.8	52.9	63.9	51.6	48.9	59.4	46.9	44.2	55.3		

	Investment Cost (% Change from Baseline in 2050)	**Capacities** (% Change from Baseline in 2050)
Fuel Cells		
High R&D	*-42.9*	*53.1*
Zero GERD	*32.8*	*-10.1*

Fuel Cells are particularly influenced by the R&D scenarios. They end up with double costs and substantially lower capacities in the zero GERD case, but display double capacity in the "High R&D" scenario. Contrary to their limited prospects in the baseline (where they fail to gain any significant market share), the "High R&D" scenario has resulted in sufficient improvements to their technical and economic performance, taking them beyond "niche" markets. Particularly, in the case of Fuel Cell cars most baseline scenarios implied virtually no penetration, while the High R&D scenario produced shares in the vehicle stock of around 15 to 20 percent by 2050, by which time fuel cell cars would gain 25 to 30 percent of total new registrations. In fact, in the High R&D scenario other non-conventional vehicles such as Hydrogen Internal Combustion Engine, Hybrid and pure Electric vehicles, though registering improved cost and technical performance, end up with lower shares than in the reference case due to crowding out from the success of Fuel Cell cars. Photovoltaics, being a relatively R&D dependent and fast learning technology, also register gains in capacity in the High R&D case, as simulated by most models.

As a broad conclusion of the analysis, the most significant effect of the elimination of the public energy R&D investment is the delay in the development of 4th generation nuclear reactors. As a consequence, one of the few ways that the energy system can meet rising demand (while responding to the climate policy assumed to apply in the outlook) is to rely more heavily on second and third generation nuclear reactors, with some additional generation from conventional coal, gas turbine in combined cycle (with and without sequestration) technologies and to a lesser extent from biomass thermal.

On the other hand, the additional R&D investment creates a more effective and competitive way of meeting climate change mitigation goals and reducing reliance on fossil fuels. This can be almost entirely attributed to the dominant impact of the additional R&D on new nuclear and to the boost in competitiveness of nearly all renewable technologies (Biomass Gasification, Decentralised Photovoltaics, Wind Turbines on- and off- shore).

Such shifts to alternative technological development paths also have implications for sustainable development, particularly since there appears to be greater reliance on low- and zero-emissions fuels under the "High R&D" scenario. The following section examines the impacts of the scenarios on indicators of sustainable development.

3.2.2. Impact of Scenarios on Sustainable Development Policy Objectives

The table below presents the impacts of the alternative R&D scenarios relative to the baseline, with respect to nine SD indicators.

Table 5: Comparison of R&D Scenarios with Baseline

SD INDICATORS (2050)		**High R&D**	**Zero GERD**
Cumulative CO2 Emissions	*(% Change)*	**-0,9 *to* -1,2**	**0,2 *to* 0,5**
Atmospheric CO2 Concentration	*(% Change)*	**-0,4**	**0,2**
Global Temperature Change	*(Δ° C)*	**-0,002 *to* -0,008**	**0,003 *to* 0,006**
Highest Temperature Change per decade 2000-2050	*(Δ° C)*	**-0,002**	**0,001**
Oil Resources/Production Ratio	*(Δyr)*	**2 *to* 9**	**-3 *to* 0**
Gas Resources/Production Ratio	*(Δyr)*	**-3 *to* 6**	**-3 *to* 0**
Share of Low Emission Vehicles	*(Change in Share)*	**8 *to* 15**	**-3 *to* -6**
Discounted Cost of Energy to Final Users (Europe)	*(% Change)*	**-0,4 *to* -2,2**	**0,2 *to* 0,7**
Discounted Cost of Energy to Final Users (LDCs)	*(% Change)*	**-0,8 *to* -3,2**	**0,5 *to* 1,5**

In terms of cumulative CO_2 emissions and atmospheric CO_2 concentration the results from the models indicate relatively limited impacts in both the “High R&D” and “Zero GERD” scenarios. Regarding the former, the reductions in energy-related CO_2 emissions over the 2050 horizon in the “High R&D” case range from 0.9 to 1.2 percent whereas the elimination of government energy R&D results in increases in emissions ranging from 0.2 to 0.5 percent. The “High R&D” scenario produces reductions in CO_2 atmospheric concentrations by 0.4% whereas the “Zero GERD” scenario results in moderate increases (0.2%).

Committed global temperature in 2050 (including a 15-year commitment period) is reduced by 0.002 to 0.008°C (relative to 2000) in the “High R&D” scenario and increased by 0.003 to 0.006°C in the “Zero GERD”. As regards the highest temperature change in any one decade of the forecasting period, the former scenario suggests a maximum decrease of 0.002°C/decade while the latter case indicates an increase of up to 0.001°C/decade.

The impacts of the scenarios on the indicators of security of energy supply are stronger. Under the R&D intensive outlook as implied by the “High R&D” scenario, the resources to production ratio for oil is extended by 2 to 9 years, indicating an important reduction in vulnerability to oil supply disruptions. On the other hand, the withdrawal of public energy-related R&D support throughout the outlook leads to a reduction in the oil r/p ratio by up to three years. In the “High R&D” scenario, some models indicate an extension to the gas r/p ratio by up to six years, whereas some indicate a reduction in the ratio (up to 3 years). This can be mostly attributed to the uncertainty surrounding the development of gas-substituting or gas-based technologies, the deployment of which will alleviate or respectively intensify pressure on natural gas resources.

The “High R&D” scenario implies substantially increased market penetration rates (8 to 15 percent increase) for low emission vehicles, whereas the elimination of government R&D radically hinders their diffusion (3 to 6 percent reduction).

Of particular interest for the R&D scenario analysis are the impacts in terms of energy cost reduction to consumers in Europe and Less Developed regions. The impacts for the “High R&D” case represent reductions ranging from 0.4% to 2.2% for the European consumers and 0.8% to 3.2% for the consumers in developing countries, while the increases for the zero GERD case range from 0.2 to 0.7 percent for the former region and from 0.5 to 1.5 percent for the latter. The energy cost reductions as implied by the upper range of the “High R&D” case indicate that the initial investment in research is more than covered by the long term reductions in the cost of energy to the consumers in these two regions.

The general consensus arising from the analysis is that the impact of R&D on more traditional objectives is strong but may appear limited for some of the SD targets, despite copious efforts to endogenise as much learning (historical and future) as possible. This outcome arises from three broad categories of reasons, namely the enormity of the issues associated with most of the SD objectives, the existence of ‘built-in stabilisers’ in model structures and baseline assumptions, and finally from problems of targeting of R&D effort. A number of factors operate to mitigate the impacts of R&D scenarios. Key among them is that learning as modelled tends to slow down as the technical possibilities of improvement are exhausted. Also, reductions in costs of energy services that can be attributed to their increased overall efficiency could also potentially encourage their use. Secondary effects on prices play a significant role: reductions in consumption may also lead to lower prices. Inter-option competition tends to neutralise some of the impacts.

All the above caveats notwithstanding, the analysis has demonstrated that the benefits arising on some of the objectives are sufficiently large to more than cover the costs of the policy.

3.3. Standardised R&D and D&D Shocks

3.3.1. Introduction

Standardised R&D and D&D shocks[6] were basically performed in order to provide the essential numerical input for the ISPA meta-model, the policy integration tool that is used to carry out policy exploration. Since ISPA is specified as an R&D portfolio exploration tool involving hedging the stochastic properties of R&D infusions had to be examined alongside expected impacts. The provision of essential input to the ISPA tool apart, the R&D shock exercises provide useful insights on the comparative productivity of R&D on specific technological options as it emerges from model results and given the R&D objectives retained in the SAPIENTIA project. Since the impact of R&D expenditure on specific technologies is stochastic, this input takes the form of joint probability distributions of the productivity of R&D expenditure on individual technologies in terms of each of the objectives under consideration.

The main vehicle of transmission from the R&D shock to a desirable effect on the indicator is the R&D term of the Two Factor Learning Curve, variants of which have been incorporated in all models participating in the project. For most models the exercises were limited to shocks of 10% of cumulative R&D on specific technological options (an exception was made for PROMETHEUS where non-linearities were examined by varying the size of the shock – see below). The shocks were applied orthogonally (i.e. affecting one technology at a time) at the beginning of the forecast horizon. Each modelling team has performed a full model sensitivity run for each technology considered. Each one of those runs has produced a new set of values for the different objectives thus telescoping the whole model mechanism linking the TFLC of that particular technology to the impact of the sustainable development indicator representing that objective.

In the sections below, the methodology for the measurement of the impacts is presented, followed by a summary of some key results derived from the analysis with the stochastic model and the deterministic models in turn.

3.3.2. Measurement of the impacts

The research productivity has been defined as the change in the SD indicator divided by the sum allocated to the option. The following general formula was used for the measurement of the impacts:

Impact on objective of technology *i* = (Change in objective measured in specific units) / (Change in R&D expenditure measured in €)

Considerable care has been devoted to provide precise and meaningful definitions of the impacts on each indicator. This section presents the specific measurement for each of the twelve objectives retained for integrated policy assessment.

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[6] Standardised increases on R&D/D&D for each technology

Measurement of the impact on climate change objectives

i. Cumulative CO_2 and CH_4 emissions

The climate change problem is global and the variables of interest are cumulative world emissions. The formula for the measurement of the impact on cumulative CO_2 and CH_4 emissions of the R&D policy in a technology is:

Impact = (Change in cumulative emissions relative to reference) / (R&D expenditure shock)

The Global Warming Potential factors for CH_4 were obtained from the IPCC Third Assessment Report on the basis of 100-years commitment horizon.

ii. Temperature change

According to the IPCC Third Assessment Report, the climate system requires some years to come into equilibrium with a change in forcing (a change in greenhouse gas emissions/concentrations for instance); there remains a "commitment" to further climate change even if the forcing itself ceases to change. In the models, a 15-year "commitment" period is considered, meaning that in order to measure more fully the temperature change implications of concentrations in 2050, the results in 2065 should be considered, under the hypothesis that all increases in concentrations cease from 2050 onwards. Thus, the formula for the impact on temperature change is:

Impact = (Shock temperature 2065 – reference temperature 2065) / (R&D expenditure shock)

iii. Highest Temperature Increase over a decade

The German Advisory Council on Global Change has conducted various surveys in which it concludes that an increase beyond 0.2oC in a decade will potentially have large ecological and economic impacts. As a measure of this damage on ecosystems, an indicator called "the highest temperature increase over a decade" has also been introduced. The impact on this objective is measured as:

Impact= (Shock highest temperature increase – reference highest temperature increase) / (R&D expenditure shock)

Measurement of the impact on security of supply objectives

i. World resources to production ratios for oil and gas

In the initial set of sustainable development objectives the Reserves to Production ratio was proposed as a measure of sustainability, vis-à-vis depletable resources. However, in trying to implement this objective it was found that these ratios were heavily dependent on projected discoveries. Since SAPIENTIA does not consider exploration technologies through which the reserves could be influenced, it was considered clearer and preferable to use an alternative measure incorporating both discovered and undiscovered reserves (the modified R/P ratio). Thus, the impact on this objective is given by the following formula:

Impact = (Shock Modified R/P ratio 2050 – Reference Modified R/P ratio 2050) / (R&D expenditure shock)

All quantities are calculated for the year 2050. In the case of oil, reserves and production include both conventional and non-conventional oil.

ii. World dependence on Middle East Oil Production

The impact on this objective is given by using the general formulation:

Impact = (Change in the 2050 Middle East ratio relative to reference) / (R&D expenditure shock)

The Middle East ratio is defined as the rate of Middle East to World Oil production in 2050.

iii. Maximum Increase in oil and gas prices in any 3-year period

This indicator has been retained from the SAPIENT project, where it was used as the sole security of supply objective:

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)

This objective was found to display high differentiation from the other objectives (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 hence susceptible of introducing interesting elements in the R&D strategy analysis to the extent that different priorities are attached to it.

Measurement of the impact on urban environment

i. Introduction of low emission passenger cars

This objective is defined as the share of fuel cells, electric, hybrid and H_2 Internal Combustion Engine cars in the world passenger car stock in 2050. The measurement of impact on this objective follows:

Impact = (Shock Low Emission vehicles – Reference Low Emission Vehicles) / (R&D expenditure shock)

Measurement of the impact on consumers and regional imbalances

i. Energy cost reduction to consumer

This objective is retained separately for Europe and for the developing World. The impact formula is given by:

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

Total energy and electricity were treated as separate objectives. This was done in recognition of the fact that total energy includes what could be termed as less essential services (e.g. private car transport) while electricity is deemed to be an essential element of comfort and development.

All final energy consumers (households and firms) are considered in the calculation. Attention was paid to avoid double counting (i.e. costs of inputs to power generation or hydrogen production have not been included as they would be properly reflected in electricity and hydrogen prices to final consumers). The social discount rate used is 4%.

Measurement of the market impact

This objective is represented by a composite index of two desirable outcomes, namely a technological cost reduction and the increase in sales volume. Costs cover capital costs, fixed Operation and Maintenance costs, variable Operation and Maintenance costs and efficiencies. The impact is measured as:

*Impact = cumulative discounted ((reference cost–R&D induced cost)*change in production volume) / (R&D expenditure shock)*

The production volume change is defined as the increase in electricity production, hydrogen production or vehicle kilometres between the shock and the reference scenario, for the electricity, hydrogen and passenger car technologies respectively. The social discount rate used is 4%.

3.3.3. The impact of R&D shocks

It was initially envisaged that the mean expected impacts for input to ISPA would be given by the analysis from the large deterministic models participating in the project, whereas the PROMETHEUS stochastic energy model would be used to obtain joint probability distributions of the impacts and other distribution parameters (notably the variance covariance matrices of the impacts). Naturally, this presupposed that the differences in the expected values of the impacts derived from the deterministic models were not large, allowing for compromise values to be decided upon for inclusion in ISPA.

Despite the fact that most models used very similar technology dynamics modules (Two Factor Learning Curves) and that homogenous measures of impacts and standardised shocks were adopted, results differ sufficiently (often widely) between the models. This is mainly due to differences in:

- Model Coverage
- Model Logic (perfect foresight optimisation, simulation, stochastic)
- Underlying assumptions
- Model parameters

Therefore averaging the impacts from the different models would lead to incompleteness and inconsistency when used for integrated policy exploration. As a result, only PROMETHEUS results were finally used for integrated policy assessment, to ensure internal consistency and correspondence between expectations and probability distributions of impacts.

PROMETHEUS results on the impacts of the R&D objectives

The table below summarises some key PROMETHEUS results on the impact of R&D shocks applied to a selection of power and non-power technologies with respect to a selection of objectives.

Table 6: Key Statistics for a selection of objectives (Source PROMETHEUS)

SD OBJECTIVE		Biomass Gasification Power Plant	Building Integrated PV	Electric-Hybrid Car	Fuel Cell	Integrated Coal Gasification	New Nuclear	Nuclear	Wind
MARKET IMPACT	Mean	0,55	0,59	0,47	13,08	0,77	0,44	0,17	0,99
	Std. Dev	*0,39*	*0,40*	*0,14*	*27,94*	*0,42*	*0,38*	*0,06*	*0,77*
TEMPERATURE CHANGE	Mean	-0,21	-0,01	-0,04	-0,01	0,16	-0,05	-0,06	-0,17
	Std. Dev	*0,17*	*0,01*	*0,02*	*0,03*	*0,13*	*0,06*	*0,03*	*0,14*
MAXIMUM TEMPERATURE CHANGE IN ANY DECADE	Mean	-0,05	0,00	-0,01	0,00	0,03	-0,01	-0,01	-0,03
	Std. Dev	*0,05*	*0,00*	*0,01*	*0,01*	*0,04*	*0,02*	*0,01*	*0,04*
MAXIMUM INCREASE IN OIL& GAS PRICES IN ANY 3-YEAR PERIOD	Mean	-10,49	-1,80	-158,82	-91,05	-42,49	-30,84	-4,97	-19,57
	Std. Dev	*23,84*	*3,42*	*197,69*	*237,29*	*63,11*	*66,55*	*6,89*	*33,02*
OIL R/P RATIO	Mean	-1,12	0,46	39,76	40,62	0,09	2,06	-0,22	-0,56
	Std. Dev	*2,99*	*0,73*	*36,04*	*81,91*	*12,47*	*6,51*	*1,08*	*4,02*
GAS R/P RATIO	Mean	8,01	0,57	-13,16	-24,90	45,11	37,93	5,13	24,59
	Std. Dev	*12,81*	*2,42*	*9,11*	*33,07*	*36,38*	*41,34*	*3,60*	*25,40*
INTRODUCTION OF LOW EMISSION VEHICLES	Mean	-0,01	0,00	2,08	0,54	-0,01	0,00	0,00	0,01
	Std. Dev	*0,01*	*0,00*	*1,37*	*1,03*	*0,16*	*0,00*	*0,01*	*0,05*
ENERGY COST REDUCTION TO CONSUMER (EUROPE)	Mean	-0,53	1,18	-3,89	-1,33	-1,90	-0,40	-0,94	-3,43
	Std. Dev	*0,45*	*0,50*	*1,43*	*2,35*	*0,75*	*0,47*	*0,22*	*2,32*
ENERGY COST REDUCTION TO CONSUMER(REST OF THE WORLD)	Mean	-0,14	0,08	-0,71	-0,28	-0,99	-0,13	-0,17	-0,47
	Std. Dev	*0,18*	*0,08*	*1,43*	*0,47*	*0,38*	*0,19*	*0,06*	*0,60*
ELECTRICITY COST REDUCTION TO CONSUMER (Europe)	Mean	-0,29	1,16	0,27	-0,09	-1,58	-0,36	-0,84	-3,10
	Std. Dev	*0,29*	*0,48*	*0,16*	*0,15*	*0,67*	*0,42*	*0,20*	*2,02*
ELECTRICITY COST REDUCTION TO CONSUMER (Rest of the world)	Mean	-0,08	0,08	0,00	-0,12	-0,91	-0,11	-0,14	-0,38
	Std. Dev	*0,12*	*0,08*	*0,02*	*0,19*	*0,35*	*0,17*	*0,05*	*0,52*

A first look at this table indicates that some technologies like Nuclear (second and third generation), Integrated Coal Gasification but also the Electric and Hybrid cars display relatively low variability for most targets. Starting with the market impact, the results indicate that with the exception of Fuel Cells impacts on this target are moderate and in general present low volatility across technologies. Fuel Cells are characterised by very high albeit very uncertain prospects. From a risk aversion standpoint, the electric-hybrid car and conventional nuclear power display more attractive prospects, as their market impacts are associated with lower uncertainty (as measured in terms of standard deviation).

In terms of impact on temperature change, biomass gasification and wind power present the largest impacts, but with relatively high variability. Hybrid electric vehicles and conventional nuclear appear more productive in mitigating temperature increases, as even though they display weaker impacts, these are associated with five to eight times less risk. Integrated coal gasification produces the most significant adverse impacts, yet with somewhat higher variability. Similar impacts are obtained for the maximum temperature change in any decade target, but in this case the Biomass Gasification power plant is a less uncertain option.

Impacts on security of supply targets are apparently much more volatile in line with considerable uncertainties surrounding world oil and gas resources and variability in oil prices. Regarding the maximum increase in oil and gas prices in any 3-year period, R&D expenditure on some technologies like fuel cells, electric/hybrid cars, integrated coal gasification and new nuclear is found to be very productive but with highly uncertain prospects. When variability is accounted for, the electric and hybrid cars have the best expectation to variability ratio, followed by 2nd and 3rd generation nuclear power which exhibits restricted impact but is accompanied by very low volatility relative to other options. As regards the oil r/p ratio, R&D on electric/hybrid cars and fuel cells present almost equal security of supply benefits; the former technology however registers less than half the variability, thus suggesting a superior performance. With regard to gas security of supply, new nuclear and wind have very good prospects which are however affected by considerable uncertainty; on the other hand integrated coal gasification presents more attractive prospects demonstrating the greatest impact with moderate uncertainty levels. Conventional nuclear is advantageous to gas security of supply, displaying fairly good prospects with low uncertainty.

Turning to the introduction of low emission vehicles, electric-hybrid cars and fuel cell vehicles (to a lesser extent) make substantial inroads to the clean passenger car market under moderate uncertainty conditions.

Concerning energy and electricity cost reduction to consumers in both Europe and the Rest of the World, integrated coal gasification produces the highest cost efficiency, followed by conventional nuclear. Wind turbines are more efficient for European rather than RoW consumers, but their prospects are somehow moderated by the associated risk in both regions. Fuel cells, new nuclear and biomass gasification power plants display higher variability, of a similar relative order among them. The electric/hybrid car displays important energy cost savings for consumers in both regions. For the electricity costs to the consumer targets however, this technology produces increases in costs for the European consumers and no changes in cost for those in less developed countries. Strong positive impacts to the energy bill are also derived from building integrated photovoltaics for both European and Less Developed countries.

As a broad conclusion of the preceding analysis, it can be argued that technologies which exhibit strong mean expected impacts are not necessarily the optimal candidates for R&D funding, as these prospects may be surrounded by higher uncertainty.

Another key element for the integrated R&D policy analysis as performed in SAPIENTIA, is the co-variance of impacts, as it greatly modifies hedging characteristics. It may also hinder or assist in satisfying given probability constraints. The main sources of covariance of impacts are:

- (Dis)similarities of conditions favouring the impact of given technologies.
- Competition between technologies.
- Technological affinity.
- Clustering and spillovers

Table 7: Market impact objective: Technology correlations (Bold figures mark correlations greater than 0.4; red highlights significant negative correlations)

	Biomass Thermal	Biomass Gasification plus cc	Hydrogen from Biomass Pyrolysis	Coal Conv. Thermal	Building Integrated PV	Electric/ Hybrid Car	Fuel Cell	Gas Turbine	CO2 capture (gas)	Integrated Coal Gasification	New Nuclear	Nuclear	Supercritical Pulverised Coal	Solar Thermal
Biomass Gasification plus cc	**0.88**													
Hydrogen from Biomass Pyrolysis	-0.19	-0.23												
Coal Conventional Thermal	**-0.63**	**-0.72**	0.29											
Building Integrated PV	0.34	0.37	-0.16	**-0.44**										
Electric/Hybrid Car	-0.02	-0.02	-0.18	0.05	-0.02									
Fuel Cell	0.01	0.01	**0.54**	0.00	0.01	-0.38								
Gas Turbine	**-0.68**	**-0.77**	0.30	**0.91**	**-0.48**	0.07	-0.01							
CO2 capture (gas)	0.26	0.28	-0.11	-0.23	0.10	0.05	-0.01	-0.25						
Integrated Coal Gasification	**-0.71**	**-0.81**	0.33	**0.89**	**-0.47**	0.08	0.00	**0.93**	-0.25					
New Nuclear	**-0.50**	**-0.57**	0.27	**0.60**	-0.20	0.02	0.02	**0.62**	-0.18	**0.64**				
Nuclear	**-0.46**	**-0.52**	0.17	**0.65**	-0.29	0.08	-0.01	**0.71**	-0.18	**0.63**	0.28			
Supercritical Pulverised Coal	**-0.60**	**-0.68**	0.29	**0.80**	**-0.42**	0.05	0.01	**0.82**	-0.19	**0.84**	**0.55**	**0.63**		
Solar Thermal	**0.63**	**0.70**	-0.27	**-0.66**	**0.72**	-0.04	0.00	**-0.72**	0.20	**-0.73**	**-0.46**	**-0.47**	**-0.64**	
Wind Offshore	**0.67**	**0.77**	-0.26	**-0.66**	0.28	-0.02	0.03	**-0.72**	0.30	**-0.74**	**-0.53**	**-0.53**	**-0.62**	**0.64**

The previous table gives the correlation matrix for the market impacts of different technologies, as an indicative measure of their stochastic interdependence as it arises from PROMETHEUS runs. In broad terms, impacts display strong correlations. Clean coal technologies (Integrated Coal Gasification, Supercritical Pulverised Coal) have more closely correlated impacts since they depend on similar configurations for making substantial inroads. The same applies to Fuel Cells and Hydrogen from Biomass Pyrolysis. Integrated coal gasification and gas turbine technologies display strong positively related market impacts, in view of the close correlation of their technical and economic characteristics (technological affinity). On the other hand, the market prospects of wind turbines offshore are negatively correlated to those of integrated coal gasification technologies, as favourable conditions for the former (for instance a carbon constrained world) hinder the market penetration of the latter. Finally, the prospects of new nuclear technologies are strongly and negatively correlated to those of biomass related technologies, a pattern attributed to strong competition between these options.

3.3.4. Examination of Non-Linearities of Impacts

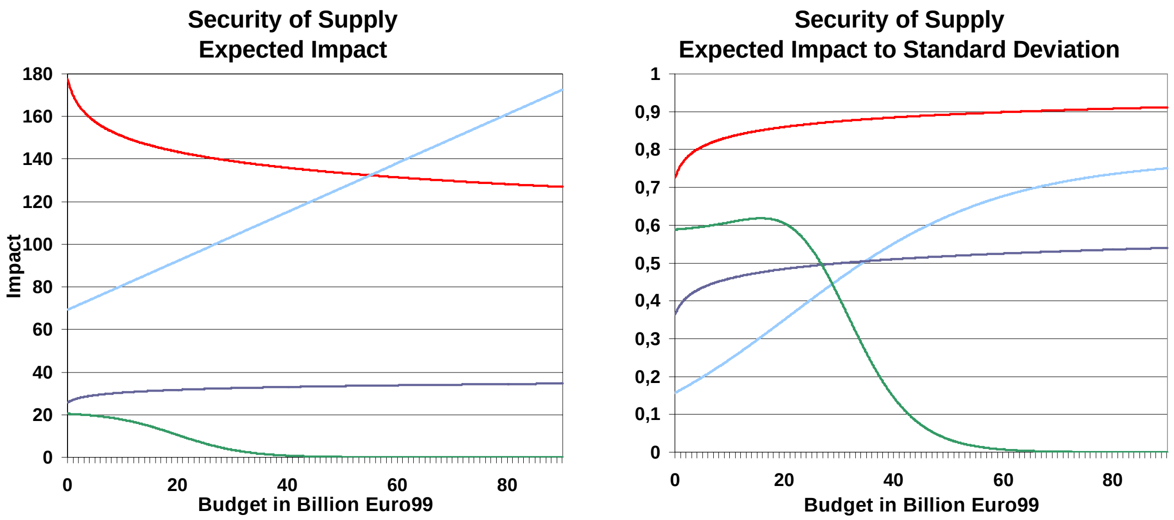
In the previous discussion R&D impacts were assumed to be linear and homogenous. The figures obtained constitute reasonable approximations of expected impacts if relatively low R&D budgets are considered. If much larger budgets must be analysed, the possibility of non-linearities in the impacts must be taken into account. This has enabled R&D budget exploration, where budget size is a possible policy parameter. In order to obtain concrete quantified information on such non-linearities, a number of R&D shock exercises were applied on 34 technologies affecting one technology at a time using the PROMETHEUS stochastic model. Each shock corresponded to the 5%, 10%, 15%, 20% and 25% of the technology's projected cumulative R&D in 2025 and it was applied to the whole period 2006-2010. 5 D&D shocks were also applied on 5 technologies (building integrated photovoltaics, fourth generation nuclear, wind turbines onshore, hydrogen internal combustion engine passenger car and gas fuel cell passenger car) affecting one technology at a time. The Demonstration shocks were equivalent in terms of value to the R&D shocks. For each shock the PROMETHEUS model was run for 1000 experiments generating a full Monte Carlo set for each technology and each shock size (resulting in 195000 runs). To examine the impact on various targets, a relatively simple and differentiable equation of the following type was fit:

Impact per unit of R&D = f (R&D shock)

Various functional form types were subsequently tested to measure the impact per unit of R&D shock. These extensive PROMETHEUS non-linearity exercises have revealed diversified (depending on technology and target) modulation of R&D impacts to budget size. Even without considering cross impacts, complexity in the representation of the non-linearities in terms of expectations and other stochastic characteristics (e.g. variance) has increased. Moreover, lock-in effects are reflected on the stochastic characteristics of the impacts announcing additional difficulties in terms of ISPA use. However, no numerical problems arise and convexity is retained. Correlations between impacts were found to be reasonably stable and largely unaffected. In general, results are defendable but impacts appear highly sensitive to budget size.

The following graphs give an indication of the non-linearities encountered and the way they have been treated. The left graph presents the variation of the expected impact per unit of R&D on the security of supply objective for four technologies, candidates for R&D funding. R&D budgeting is effectively a highly speculative activity, implying that considerable uncertainty exists on the efficacy of R&D actions; in this context the graph on the right gives another dimension to the productivity of R&D expenditure on these technologies, providing the mean impacts in terms of standard deviation, thus incorporating notions of uncertainty.

Figure 9: Security of Supply impacts: Expectation versus Variability



The first observation is that impacts as well as the standard deviations appear to be non-linear (they vary with the budget). The mean impact of R&D on Fuel Cells, is sharply increasing with the level of the research budget and so does the attractiveness of this option as measured in terms of the ratio of expected impact to standard deviation. Fuel Cells, being a high risk, high return option, require major R&D efforts to be able to exhibit strong expected impacts at declining uncertainty.

The expected impact of Electric-Hybrid cars on the security of supply target registers decreasing returns to R&D effort. However, the ratio of this impact to standard deviation was found to increase with budget size, suggesting increasing attractiveness of this option in terms of hedging on security of supply.

The productivity of additional research on wind turbines is decreasing, but this option is highly attractive under conditions of hedging, for budgets below a certain amount (approximately 20 billion euro). Beyond this level, its expected impact diminishes. This indicates that wind provides moderate but secure impacts at low levels of additional R&D effort.

3.3.5. Synthesis of results from deterministic models

This section concentrates on the deterministic model results on the impacts of R&D investment on individual technologies. The following analysis is restricted to the most and least productive technologies in terms of meeting R&D policy objectives as indicated by the broad model consensus.

Concerning CO_2 emissions reduction, coal CO_2 capture technologies and wind turbines (both onshore and offshore) appear to be the most productive technologies, followed by hybrid/electric vehicles, fuel cells, nuclear and biomass power plants. The most noticeable negative impacts are produced by coal-based technologies. As regards the global market share of clean passenger cars, results from most models indicate that the largest positive impacts are achieved by the hybrid-electric passenger car, fuel cell vehicles and the hydrogen based Internal Combustion Engine vehicle.

Turning to security of energy supply indicators, and in particular to the oil resources over production ratio, R&D shocks applied to generic fuel cells produce the most significant impacts. In addition, shocks to the electric, hybrid and hydrogen ICE vehicles and advanced nuclear power plants also enhance long-term oil security. The main reason for this is that R&D support for these technologies potentially assists their earlier deployment, providing a flexible and convenient alternative to oil consumption. R&D “shocks” applied on technologies that improve the efficiency of oil consumption, such as the hybrid battery system, also extend oil availability.

As for gas security of supply, the results from most models indicate that R&D investment targeted at technologies that contribute to a substitution of gas for other energy sources leads to enhancement in the gas r/p ratio. Indeed, the most significant positive impact on security of gas supply is produced by funding on coal and clean coal technologies, namely integrated coal gasification, supercritical pulverised coal (with and without CO_2 capture) and conventional coal technologies. Significant positive impacts are also produced through nuclear power which displaces gas-based power plants in the electricity sector. Strong negative impacts are produced by R&D on fuel cells and by the introduction of CO_2 capture in combined cycle gas turbines. The diffusion of these technologies encourages the consumption of natural gas leading to vulnerability to supply disruptions.

In terms of impact on energy cost reductions to consumers, R&D investment on integrated coal gasification produces the highest cost-efficiency for both the European and Rest of the World consumers followed by wind (both onshore and offshore), and CO_2 capture technologies. Funding on Fuel cells and the conventional ICE car perform efficiently for the European consumer, whereas the electric and hybrid car is also projected to benefit European and Rest of the World consumers but to a lesser extent. On the other hand, photovoltaics and CO_2 capture for gas technologies appear to be the least productive candidates in terms of cost reduction to consumers both in Europe and the Rest of the World.

To sum up, from a broad consensus of the different models (deterministic and stochastic) and covering all Sustainable Development objectives the technologies presented in the next table appear to be the most suitable candidates for R&D funding.

Table 8: Suitable candidates for R&D funding

Technologies	
Electric/Hybrid passenger car	Nuclear (2nd and 3d gen.)
Integrated Coal Gasification	Hydrogen from Biomass Pyrolysis
Fuel Cells	Supercritical Pulverised Coal
Wind Turbines Offshore / Onshore	Hydrogen ICE car
CO_2 capture (coal)	Biomass Gasification Power Plant

4. Integrated R&D Policy Assessment

4.1. Introduction

Central to the SAPIENTIA approach is the elaboration of a small aggregated meta-model named ISPA (Integrating System for Priority Assessment), specifically designed for R&D budgeting policy exploration. In essence, the ISPA model explores the 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 order to incorporate fully the stochastic characteristics of the problem (enable the analysis of risk averse stances) and at the same time treat the different objectives symmetrically, ISPA is specified as an optimization problem where the probability that an objective exceeds a given threshold is maximised 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.

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 is allowed for, arising from the fact that they are affected (albeit differently) by the same variables that are themselves subject to risk.
- Emphasis has been 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.

Alternative specifications are of course possible as for example setting the goal as the maximisation of the expectation or alternatively the constraints as inequalities on the expectation of the different objectives. Such specifications would result in asymmetric treatment of the objectives rendering the discussion of the presentation of the results somewhat ambiguous. Replacing both the goal and the objective in terms of expectations would effectively destroy the stochastic character of the exercise rendering meaningful risk analysis impossible.

4.2. Integrated Policy Exploration using ISPA

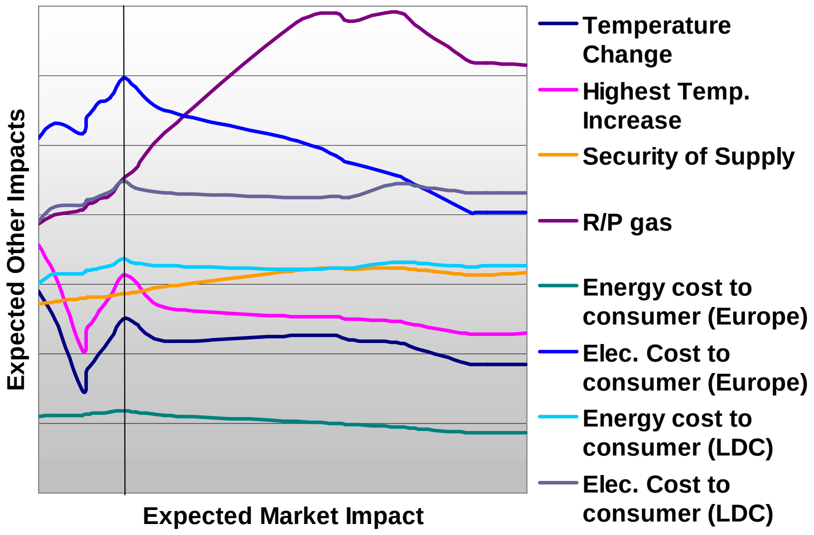
The reaction functions linking the expected impact of an R&D action on the objectives of the R&D policy along with the stochastic information (variances, co-variances of impacts, joint probability distributions of the productivity of R&D expenditure on individual technologies) as derived from PROMETHEUS in the R&D “shock” exercises (presented in the previous section) have provided the essential numerical input to ISPA, in order to perform the integrated R&D policy assessment. The set of objectives presented in section 2.1 has been integrated in the meta-model whereas 39 technological options were considered in the analysis.

The policy integration tool offers a large number of possibilities for policy exploration. To begin with, a feasible set is defined representing for each objective thresholds for the impact of R&D and minimum probabilities that they will be exceeded. The exploration proceeds by placing each sustainable development objective in the principal objective position, allowing the minimum threshold regarding it to be increased and maximising the probability of achieving it. This implies that the expectation regarding this objective is raised under conditions of hedging while satisfying minimum requirements on other objectives. This process is repeated placing other indicators on the principal objective position. Successive solutions lead to the construction of a series of pay-off curves. Of particular interest on these pay-off curves are turning points. Such turning points indicate solutions where a gain in one objective can only be achieved at the cost of deterioration on another (i.e. they mark the end of synergy on the two objectives). Sets of such solutions are collected and examined for common traits indicating robust results as well as divergences. In the presence of divergent policy mixes, “compromise” solutions could be obtained by using rules and methods developed for multiple criteria optimisation.

The exploration procedure adopted starts from the existing public R&D budget to construct the feasible set by exploiting synergies among the objectives. The solution obtained is then improved by consolidating synergies and relaxing bounds and, finally by sacrificing the probability (or the threshold) requirements for some objectives. Guidance in the relaxation and the sacrificing has been provided by the shadow costs.

For the initial exercise market impact was used as the main objective while the sustainable development objectives operating via the constraints. The market impact threshold was raised in small steps while satisfying minimum requirements on other objectives. This process led to the construction of the pay-off curves presented in the figure below. An interesting finding within this excercise has been the identification of broad synergies between expectations on the sustainable development targets on the one hand and on market impact on the other.

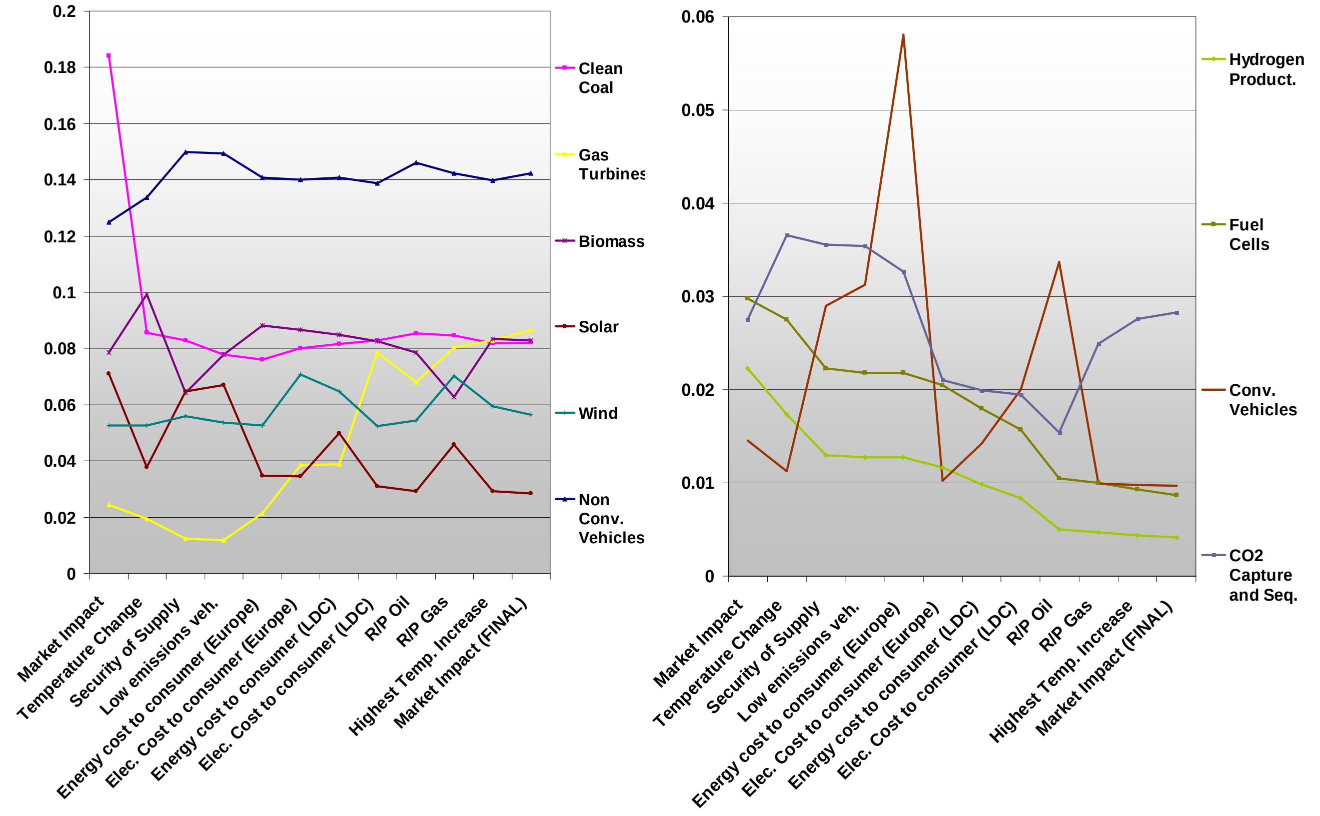
Figure 10: Example of pay-off and compromise chosen



An inspection of the pay-off curves indicates that there is a clear peak in the pay-off curves of nearly all secondary objectives, at the points where the curves are intersected by the vertical line. Beyond this point, improvements in the expected market impact are only obtained at the expense of inferior performance in terms of almost all the other objectives. For example beyond this point, the expected market impact can be improved only at the expense of energy and electricity cost reductions to the consumers in Europe and the developing world. Likewise, the expected impact on temperature change and on highest temperature increase does not grow beyond the point where their pay-off curves are intersected by the vertical line. Exception to this is the broad synergy between expectations on market impact on the one hand and security of supply on the other (notably gas security of supply) even at high levels of market impact ambition. However, this broad synergy appears to occur only at the expense of the expectations on almost all secondary objectives. In view of the above, the compromise (low regret) solution chosen is marked by the vertical line which passes through the turning points of most pay-off curves. Having found this ‘satisfactory’ (compromise) for the market impact objective solution, this solution was ‘frozen’ as a constraint and then another objective was placed in the main position, increasing gradually its expectation.

The budget allocations derived during this exploration process are presented in Figure 11 below. The budget allocation on the compromise point of the previous graph is the starting point. As the exploration proceeded by placing each other objective in the main objective position, the corresponding budget shares are presented; the market impact objective is eventually re-placed at the main objective position and the final budget shares, as shown by the final points in the graphs are derived.

Figure 11: Budget shares during the exploration process



A summary view of the budget results arising from the whole range of exercises follows. Non conventional vehicles receive the highest shares (approximately 12.5 to 15 percent) irrespective of the target that was placed as the main objective. Clean coal technologies feature strongly in almost all the cases examined (budget shares of around 8 percent), inlcuding those that gave priority to temperature change. Among renewables, biomass attracts the higher funding in all the exercises carried out (6 to 10 percent of the budget), with the exception of the case where priority is given to the gas resources to production ratio when it was overtaken by wind, (but still maintained over 6 percent of the budget). Wind gets around 5 percent of the budget in all exercises performed with the exception of the cases where the gas r/p ratio and the electricity cost to the consumer in Europe is prioritised; in these two cases wind's share rises to around 7 percent. Solar thermal in turn tends to get higher funding when security of supply, introduction of low emission vehicles and also consumer cost reductions in developing countries are set as the main targets.

Gas turbines, characterised by relatively low emissions, large and reasonably secure market penetration prospects feature strongly in the exercises when market impact, highest temperature increase, gas security of supply and electricity costs to consumers especially in less developed regions were given priority, attracting shares between 7 and over 8 percent of the budget. Their share is halved when electricity cost to the european consumer and energy cost to the developing world consumers were given priority. In the remaining cases gas turbines are directed less than two percent of the budget.

Conventional vehicles are restricted to low shares of the budget, displaying shares below 3.5 percent of the budget in most cases with the exception of the case where priority was given to energy cost reductions to european consumers, where they get a share close to 6 percent.

CO_2 capture and sequestration technologies register shares between 1.5 and 3.5 percent in the exploration exercise. They are particularly favoured when temperature change, security of supply and low emission vehicles are the dominant concern.

Fuel Cells and Hydrogen production technologies are restricted to low shares (less than 3%) irrespective of the target that was placed as the main objective. They tend to attract more funding when temperature change and security of supply were given emphasis and the least when market impact is given priority.

4.3. The MIP specification of ISPA

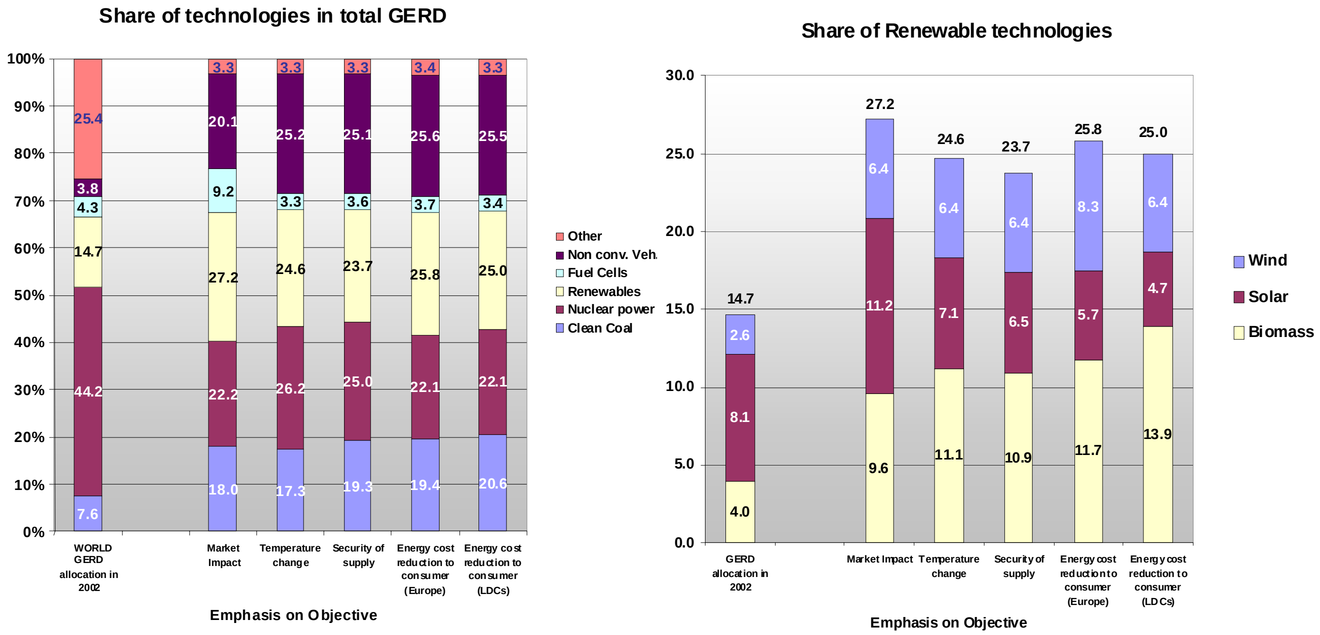
Using the PROMETHEUS stochastic model, a comparison of the impacts on SD objectives obtained by the baseline projected GERD allocation with the impacts obtained by using the ISPA allocation was delivered. The results showed that the ISPA allocation improves relatively slightly the mean values but has much greater effect on the probabilities of obtaining impacts. The solutions obtained using ISPA turn out to be highly conservative sacrificing unduly expected impact in an effort to secure minimum requirements. Part but not all of the reason why this is so, lies in the assumption of normality of the impacts distribution (which is not the case according to PROMETHEUS results). Therefore, a Mixed Integer Programming (MIP) specification has been tested, which provides complete flexibility on the joint distributions of the impacts as it can handle non-symmetric and non-unimodal distributions and take automatically into account complex co-variance patterns. In addition, no illegal values (according to PROMETHEUS or common logic) are considered. It also respects PROMETHEUS results rendering analytical walk-back feasible. This approach expands the possibilities for adopting different risk-averse stances as it has no restriction to probabilities greater than 50% and it can handle non-convexity.

However, the MIP version of ISPA has some disadvantages. Computational difficulties imply long and sometimes erratic solution times, restricting the number of possibilities that can be explored. The introduction of non-linearities of expected impacts has also posed difficulties. Finally, the possibilities for using shadow costs (dual values) to guide the exploration were limited. With familiarity with the problem useful shortcuts were found that reduced the computational time required. However, the difficulties in introducing non-linearities of expected impacts limit the MIP specification to the exploration of relatively low budgets.

The first task in the utilization of the MIP version of ISPA for budget exploration consists in specifying fairly ambitious expectations targets for all objectives. The exploration proceeds by giving emphasis on one objective at a time, seeking higher expectations and lower risks. Exploiting synergies allows to consolidate gains both in terms of expectations and risks. By setting ambitious targets on all objectives simultaneously the budgets obtained are both diversified in terms of technologies included and fairly stable, despite shifts in emphasis.

The figures below summarise the optimal budgets obtained in these sets of exercises. The share of renewables is further disaggregated on the right.

Figure 12:Exploration procedure summary results



The budget exploration exercises have been performed assuming increases to the projected public R&D allocations of a relatively modest size compared to the baseline. In this sense, they are marginal in nature and depend on the allocations assumed in the baseline. Non conventional vehicles (mostly electric and hybrid) represent five to seven times larger shares in the exploration exercise relative to their recent funding. They attract shares from 20 to 26 percent of the budget in all cases examined and appear to benefit from relative independence from impacts of allocations on other technologies. Electric and Hybrid vehicles are particularly favoured when emphasis is placed on urban transport and costs to consumers (but also security of supply and climate change) but tend to display the lowest shares when emphasis is placed on market impact (giving way mostly to fuel cells).

Nuclear power options get appreciably lower shares than recent public R&D allocations (of around 44%). They are allocated 22 to 26 percent of the R&D budget in all exercises, of which approximately 14 percent corresponds to 2nd and 3rd generation nuclear. Their prospects are more attractive when priority is given to climate change, security of supply and gas resource depletion.

Clean coal technologies feature strongly in all the cases examined, displaying double to triple shares relative to the 2002 world public R&D allocation. This group of technologies attracts 17 to 20 percent of the budget allocation in all exercises examined. Due to negatively correlated prospects with most of the other options, their support constitutes a major hedging instrument especially with regard to meeting binding probability constraints on secondary objectives. Integrated coal gasification features strongly in the solutions, displaying more attractive prospects when emphasis is placed on consumer costs in less developed countries. This technology also plays an instrumental role for meeting security of supply and gas resource depletion probability constraints (in cases of failure of 4th generation nuclear).

Renewable technologies are allocated substantially higher R&D effort in all exercises performed. Solar technologies are more effective in terms of market impact, but in all other cases their shares are markedly lower. They tend to get lower funding when energy costs to consumer are set as the main objective. On the other hand, biomass attracts low funding when market impact is given priority but is particularly favoured when energy cost reductions to consumers in the less developed countries are the dominant concern.

Fuel Cells are particularly favoured when market impact is given priority (attracting close to 10% of the budget allocation) due mainly to relatively high (albeit more uncertain) prospects to 2050. However, when emphasis is placed on other targets, their rather ambiguous and volatile impacts mean that their share falls to only 3.5% of the allocation. Carbon capture and sequestration technologies, which are characterised by relatively poor improvement prospects but are favoured already in the baseline R&D projection, attract only 0.5 to 0.55 percent of the budget, mostly playing the role of hedging against high energy costs due to possible very high carbon values.

5. Summary Conclusions

The overall analysis within SAPIENTIA indicates that R&D is broadly a cost effective way of addressing a large number of SD objectives. Some SD concerns however necessitate large scale changes and R&D alone cannot make a major impact. A certain amount of re-direction of GERD could prove effective in pursuit of sustainability on many fronts. It could also prove a fine balancing act because of important secondary effects.

Modelling energy technology dynamics has rendered quantitative integrated R&D policy exploration possible. Diversified and robust solutions emerge, taking into consideration multiple objectives, synergies of R&D actions and the structure of uncertainties. Still, a lot remains to be done in terms of dissemination of the methodology developed before it can be applied directly on R&D policy formulation.