

Endogenous Technology Modelling



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Nikos Kouvaritakis
Vangelis Panos

National Technical University of Athens

Tel: +302107723629

E-mail: kapros@central.ntua.gr



Outline of the presentation

- Introduction:
 - Why model technology change
 - Main challenges
- Learning Curves
 - Specification
 - Construction - Estimation
 - Technological Clustering
- Using models to examine induced technical change
 - R&D scenarios
- Performing Integrated R&D Budget Exploration
 - Specialised tools
 - Examples of their use



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Why model technological change?

- Most models assume (exogenous link) an evolution of the technical and economic characteristics of the different demand and supply options
 - Concentration on mechanisms of choice
- Yet technical progress:
 - Key to economic growth
 - The ability to analyse it could expand model capabilities in a variety of ways



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Enhancing models by incorporating technological dynamics

- A fuller representation of the mechanisms characterising the energy system
- Possibilities for simulating induced technical change:
 - Policies promoting and directing technological improvement
 - Becoming increasingly important in liberalised world where many forms of direct intervention tend to be excluded
- Removing bias in estimating the cost of adjustment to changing situations and policy contexts
 - Increased flexibility of adoption if technological progress responds to signals
 - Ignoring such adjustment possibilities leads to overestimation of cost



Main challenges in modelling technology dynamics

- Theoretical framework is not sufficiently established:
 - Unlike models for market behaviour no generally accepted corpus for technology dynamics exists
- Information Base problems:
 - Partly linked to inadequate definitions and a lack of theoretical framework
- Model implementation difficulties:
 - Non-convexity



Information availability

- Characterisation:
 - Disparate sources
 - Uneven coverage
- Technical Progress:
 - Not always clearly defined
 - Should include technical and economic characteristics
 - Capital costs, Fixed O&M costs, Variable O&M costs, Efficiency, etc.
 - But also quality considerations
 - Reliability, Maturity, Acceptance, etc.
- Difficulties in obtaining data on historical evolution
 - For both technical characteristics and technology uptake
- Drivers:
 - Problems in attribution of R&D effort to particular technologies
 - Indirect methods necessary to fill the gaps



Non-convexity

- Can cause model instability
 - Extreme sensitivity to initial conditions of some exogenous assumptions
- Can present computational problems in models that involve optimisation behaviour of agents



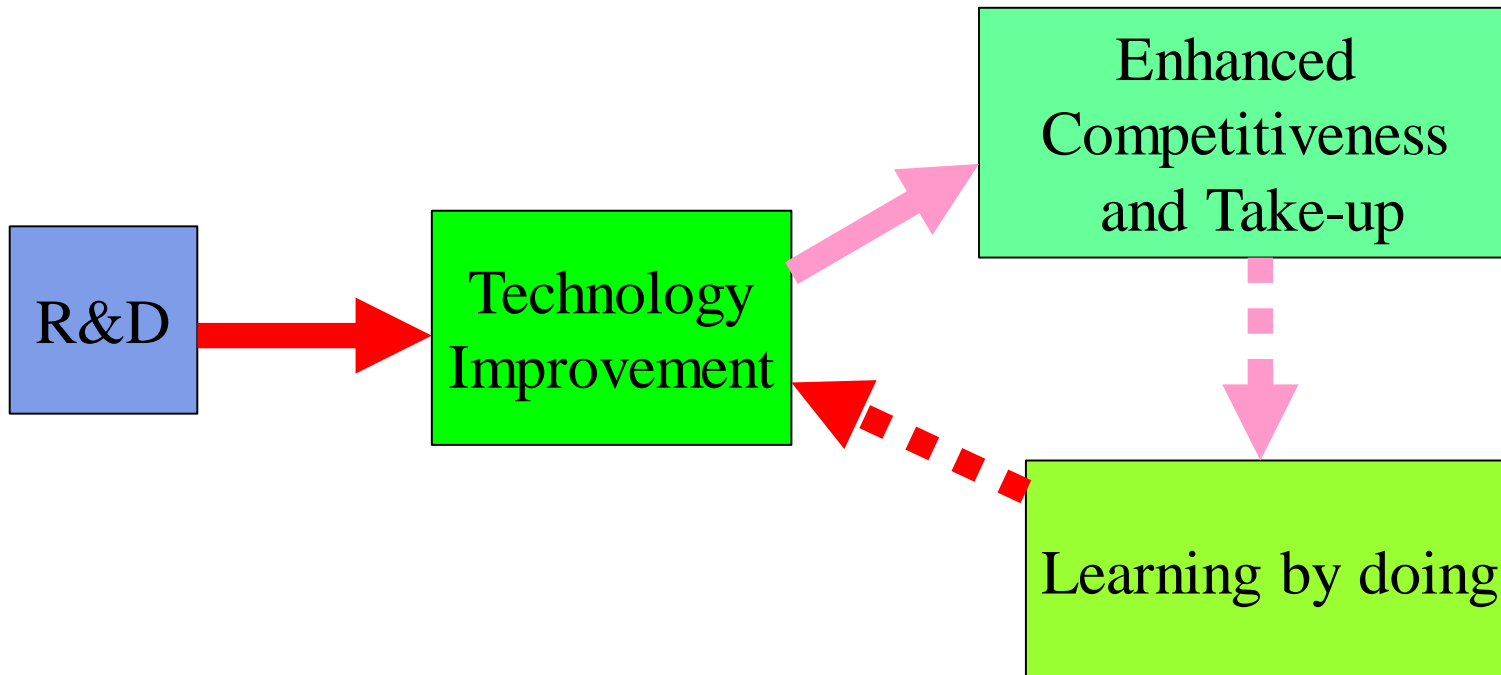
Learning curves

- Simple and widely used notion for modelling endogenous technical change
- In its simplest form describes investment cost as a function of cumulative capacity (“learning by doing”)
 - Notion of “Learning Rate”
- Need to include additional drivers for simulating induced improvements
 - Two factor learning curve (TFLC) combining learning by doing and learning by research



Two factor learning curves (TFLCs)

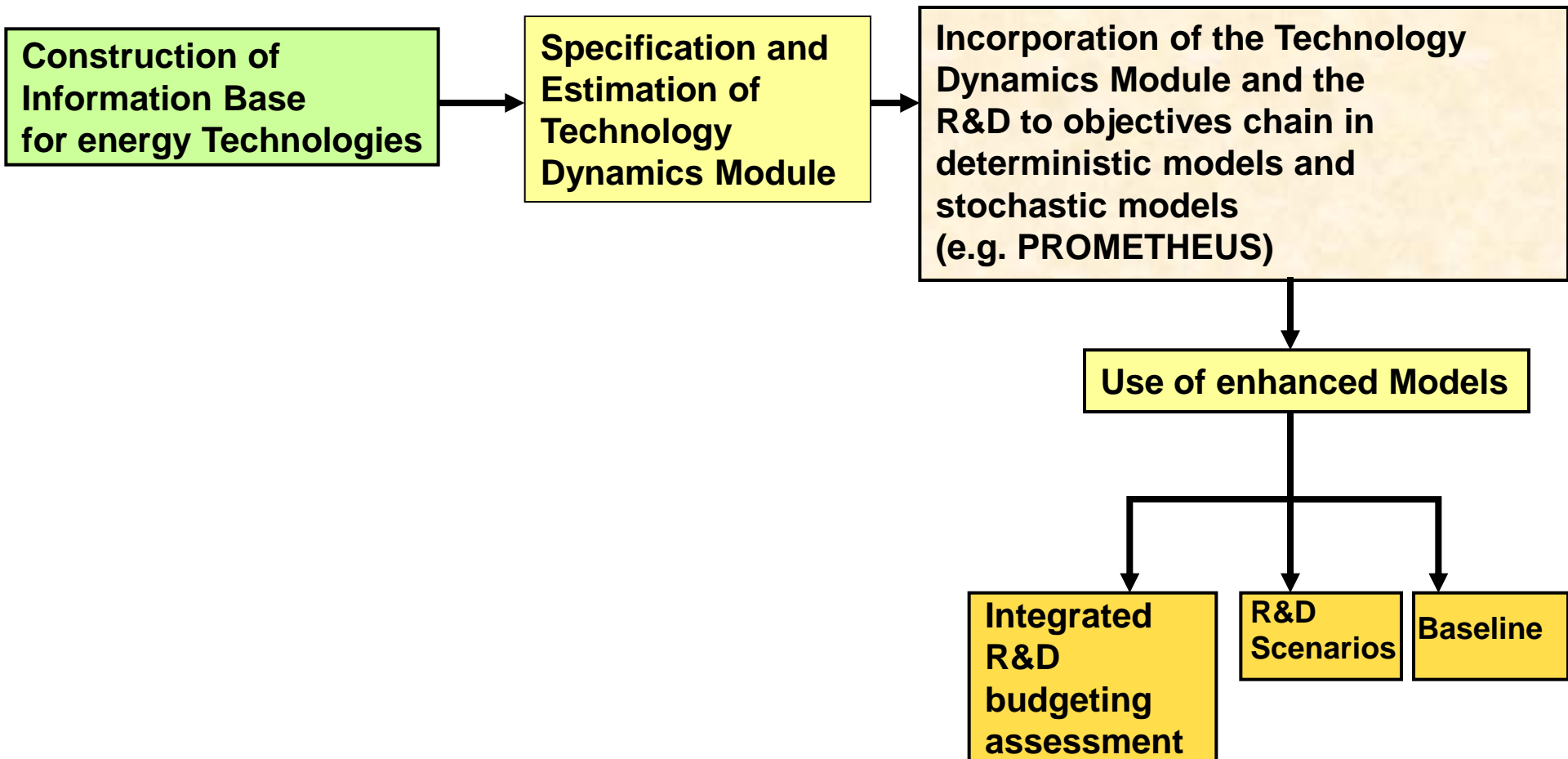
- TFLCs are crucial elements for modelling Technology Dynamics and performing the R&D scenarios. Learning by research is the first and most influential element in the chain:





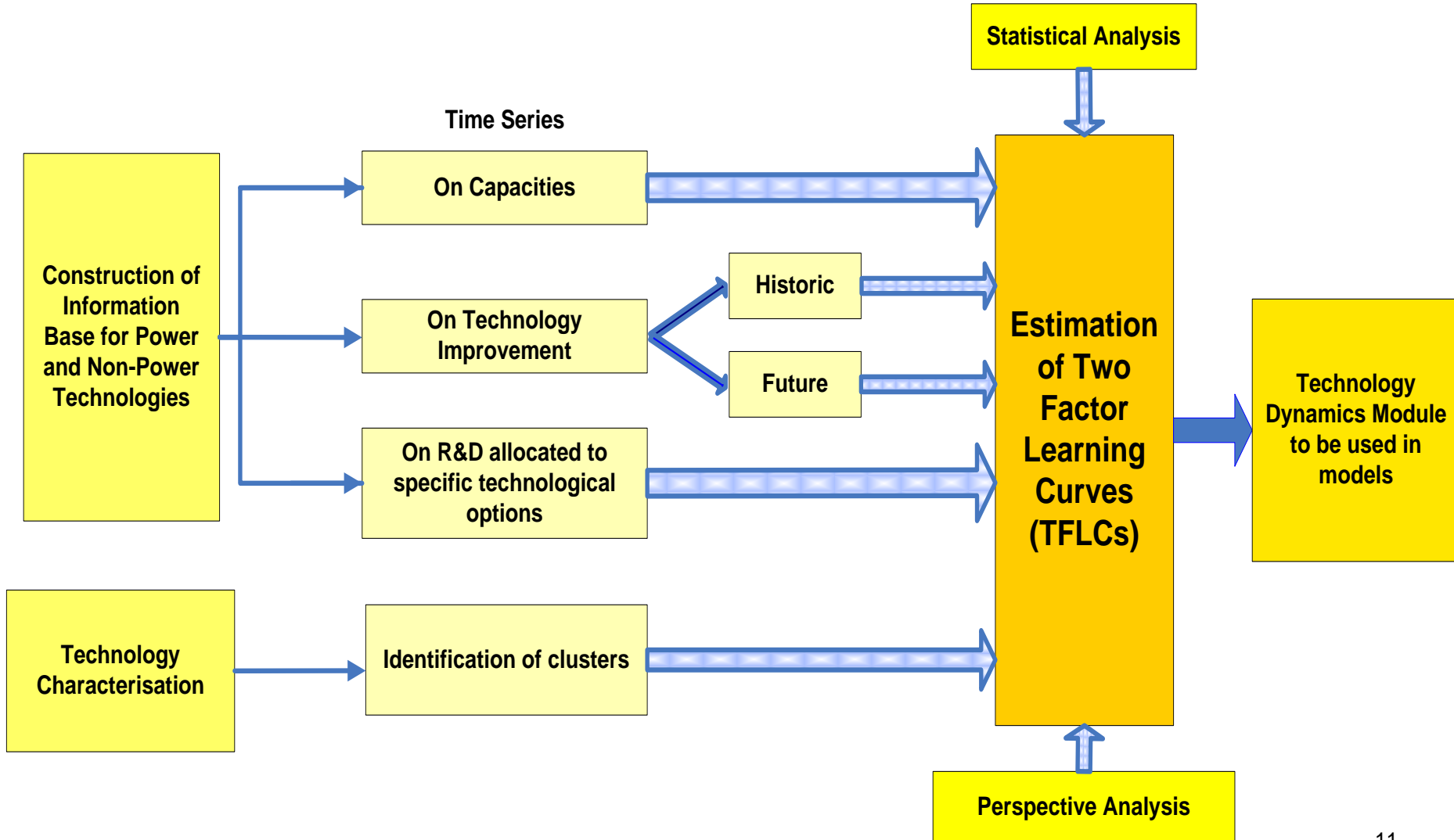
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Overview of construction and use of models to simulate induced technical change





Constructing Modules for Technology Dynamics (TFLCs)





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Properties sought in specification and estimation of TFLCs

- Both Learning-by-doing and Learning by Research
- 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 will allow
- Take carefully into account initial conditions regarding cumulative R&D and equipment stock
- Generate “unbiased” statistical properties
- Capture as much of the above with as few parameters as possible



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Algebraic Specification of TFLCs

The general formulation of a 2FLC is:

$$Cost_{i,t} = Cost_{i,t-1} \prod_{c=1}^l \left(\frac{cl_{c,t}}{cl_{c,t-1}} \right)^{r_{ic} a_t} \left(\frac{K_{i,t-1}}{K_{i,t-2}} \right)^{\left(1 - \sum_{c=1}^l r_{i,c} \right) a_t} \left(\frac{R_{j,t}}{R_{j,t-1}} \right)^{b_t}$$

c , cluster

n , number of technologies

w_{ij} , weight of technology j in cluster c

K_j , capacity of technology j

$R_{j,t}$ Cum R&D on technology j

r_{ic} weight reflecting importance of component belonging to cluster for tech i adjusted for learning rate of cluster

where,
$$cl_{c,t} = \sum_{j=1}^n w_{jk} K_{j,t-1}$$

The learning by doing and learning by research elasticity decline as cost approaches the floor cost:

$$y_{j,t} = \frac{-\text{floor}_j}{|\text{floor} - C_{i,t-1}| + 1}$$

$$a_{i,t} = \text{capelfac}_i \cdot e^{s_i \cdot y_{i,t}}$$

$$b_{i,t} = \text{rdelfac}_i \cdot e^{s_i \cdot y_{i,t}}$$

s_i , saturation rate coefficient, regulating the speed at which saturation is reached



Clusters of technologies

- Development and adoption of technologies occur as collective evolutionary processes
- Complex interactions where several technologies reinforce and cross-enhance each other drive to the creation of technology clusters
 - i.e. families of technologies evolving and diffusing together, and to the constitution of associated networks of economic and social actors.



- Clusters play an important role in technological change
- The technologies that constitute a given cluster are related by multiple links that contribute to magnify their economic, social and environmental impacts.
- These multiple relations contribute to make progress in one of them relevant, directly or indirectly, to other members of the cluster, while contributing to reinforce their own position in the marketplace.
- Learning spillovers from one technology may trigger improvements in related technologies.
- Also, performance/cost advances in a particular technology can make a whole energy chain more attractive than others.



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Examples of clustering – Power generation technologies

- Weights on the learning by doing parameter reflecting the importance of each component-cluster in learning process

	steam turbine	gas turbine	boiler	recovery CC boiler	gasifier	hydro turbine	nuclear reactor	Biomass processing
	1	2	3	4	5	6	7	8
Large Hydro						0.04		
Nuclear (2nd and 3d gen.)	0.11						0.59	
New Nuclear (4th gen.)	0.03						0.17	
Lignite Conventional Thermal	0.36		0.40					
Coal Conventional Thermal	0.36		0.41					
Supercritical Pulverised Coal	0.19		0.21					
Integrated Coal Gasification	0.03	0.17		0.07	0.46			
Oil Conventional Thermal	0.39		0.43					
Oil fired Open Cycle Gas Turbine		0.98						
Gas Conventional Thermal	0.42		0.47					
Gas Turbine Open Cycle		0.99						
Gas Turbine Combined Cycle	0.09	0.67		0.19				
Cogeneration from gas	0.09	0.79						
Small Hydro (<25MW)						0.13		
Solar Thermal Power Plant Cyliandro-Parabolic	0.07							
Biomass Thermal	0.08		0.09					0.33
Biomass Gasification plus Combined Cycle	0.03	0.14		0.05	0.37			0.27

Broad group but weak learning links

Mostly strong learning links

Influences diversified options



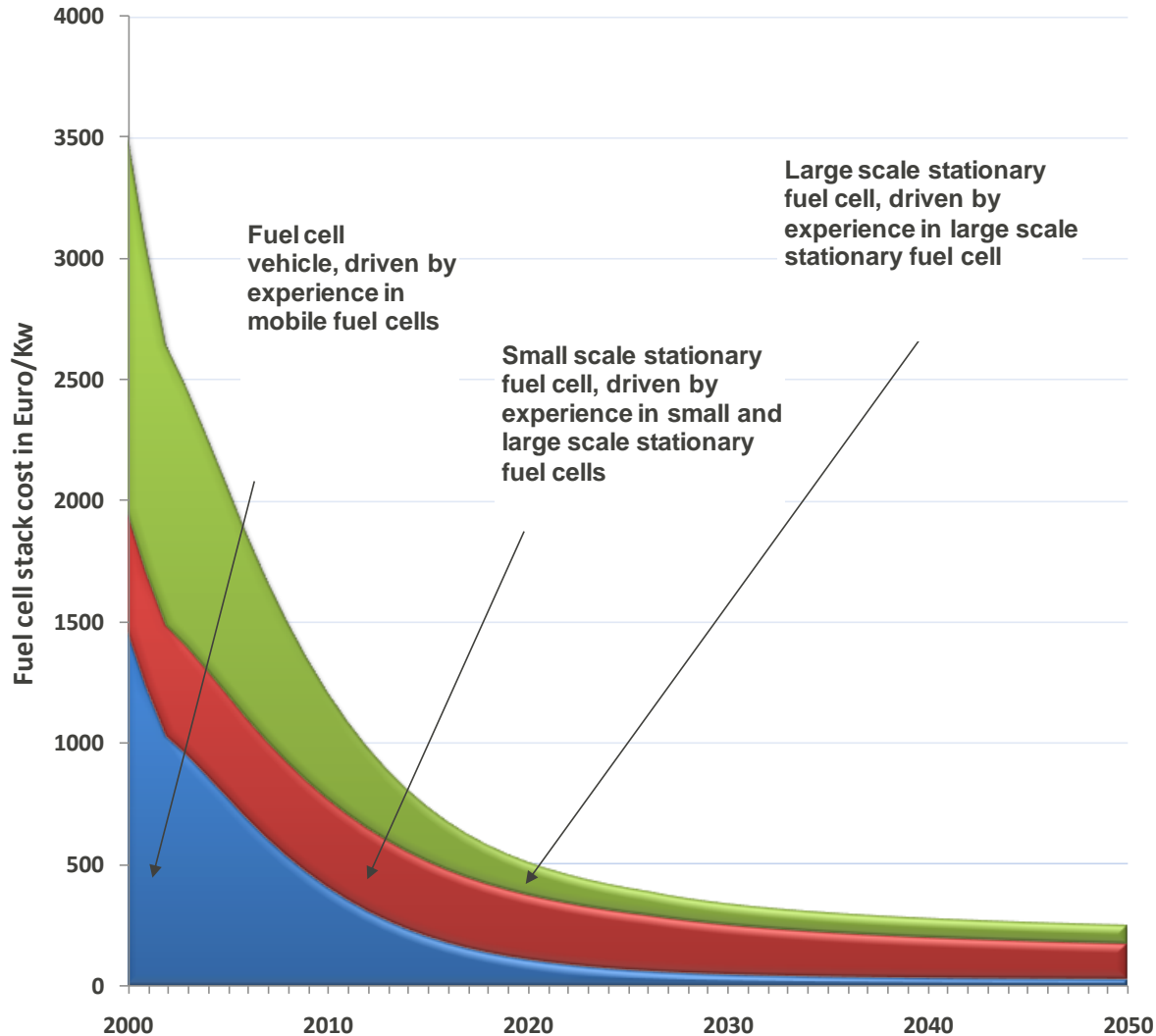
“Weak” clustering

- This form of clustering does not identify individual components, which learn separately (eg. steam turbines, boilers, gasifiers, etc.) but it uses a whole technology as the basis for other similar (and probably more complex) technologies.
- This connection is identified as “weak” because the largest part of the improvement of the technologies belonging to such a cluster is specific to each technology and independent of the progress of the basic technology



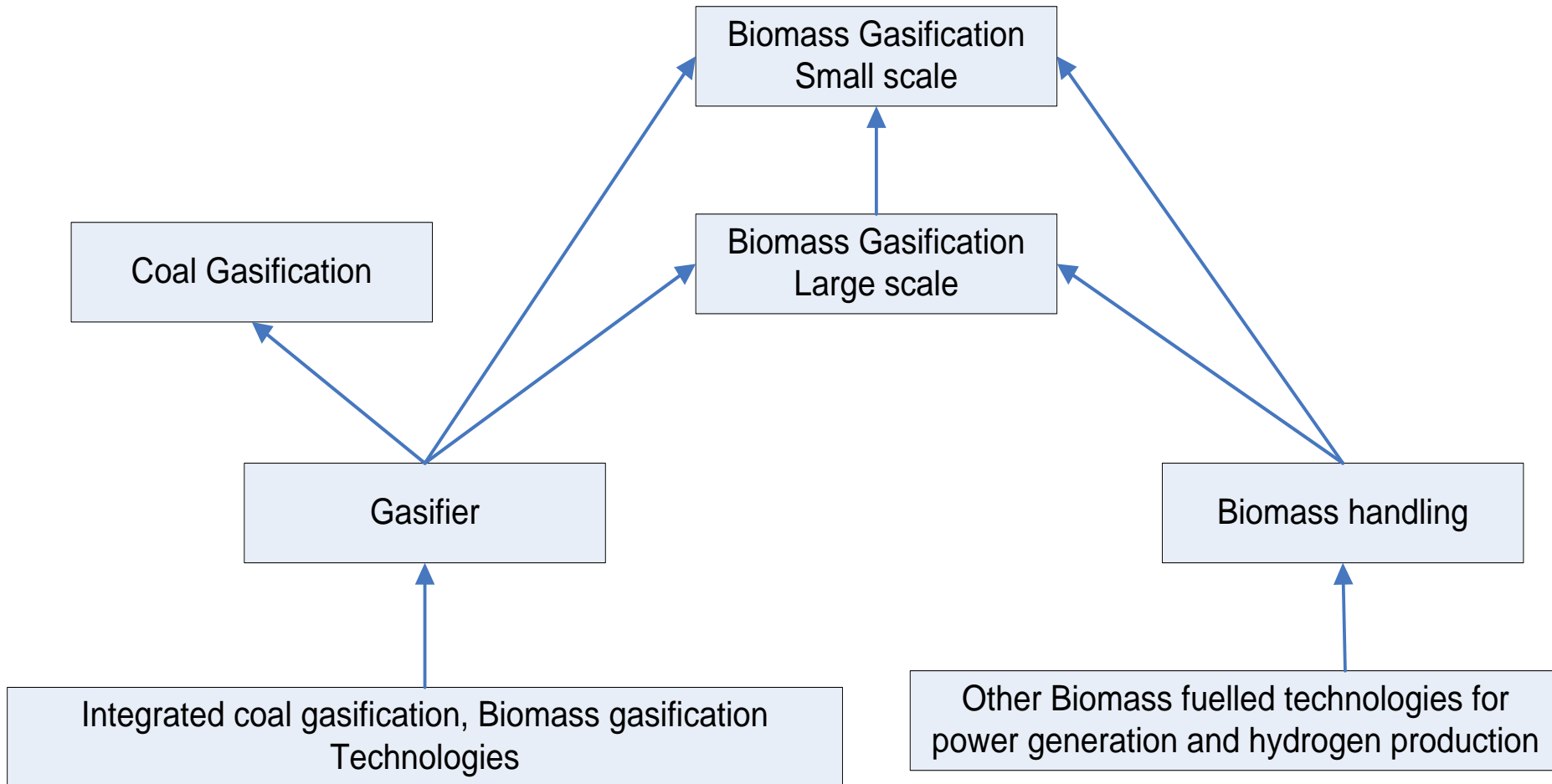
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Examples of “weak” clustering – Fuel cells stack costs





Examples of “weak” clustering – Biomass gasification for H₂ production





Estimation Method of TFLCs

- Maximum Likelihood over the historical period was one but by no means the only estimation criterion.
- All properties sought in the TFLCs figured among the objectives of the estimation.
- Simultaneous equations estimation methods used (along clusters) in order to improve estimates and obtain appropriate co-variances of learning parameters.

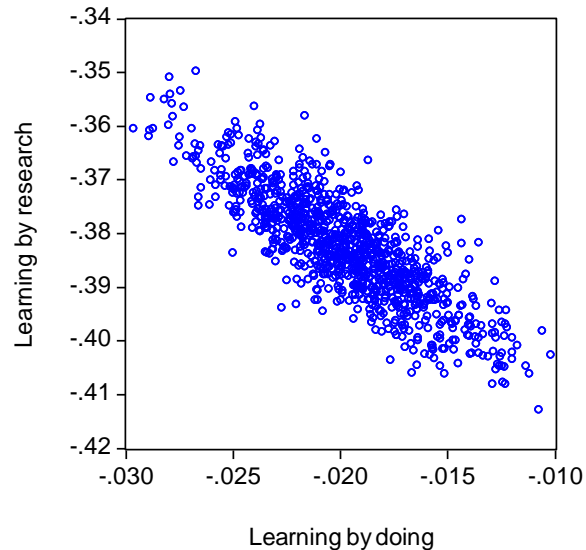


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Co-Variance in learning parameters

- In general learning by doing and learning by research parameter estimates within a single technology are strongly and negatively correlated.
 - This tends to reduce variability of learning.

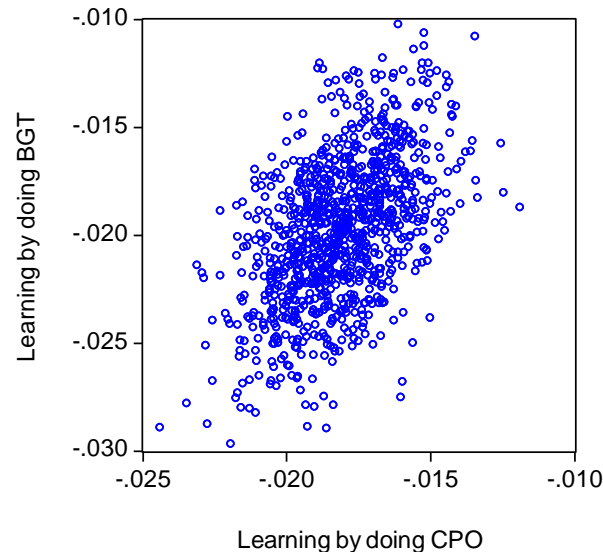
Learning by doing and learning by research for capital cost
(Biomass Gasification for power generation)





- Learning parameters 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 by doing of Biomass Gasification for power generation (BGT)
and learning by doing of Coal Gasification for H₂ production (CPO)



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



From TFLC estimation to R&D scenarios

- As a demonstration of the TFLCs as a tool for assessing R&D policy scenarios, the following scenarios are examined focusing on R&D policies on H₂ related technologies:
 - **Baseline R&D**
 - **Stop all baseline R&D expenditures on hydrogen production, infrastructure and fuel cell technologies from 2007 onwards worldwide.**
 - The purpose of this scenario is to examine the role of R&D in initiating any progress in hydrogen related technologies.
 - **Tenfold increase of baseline R&D allocations on fuel cells from 2007 to 2015 worldwide.**
 - This corresponds to about 207 billion €05 additional R&D expenditures in fuel cells.
 - **Tenfold increase in baseline R&D expenditures on hydrogen production options between 2007 and 2015 worldwide.**
 - This corresponds to 167 billion €05 of additional R&D expenditures.



Impact of additional R&D on technology costs

Mobile applications of fuel cells

	unit	2025			2050		
		Baseline	10x R&D	% change	Baseline	10x R&D	% change
Stack cost	€/kW	57	21	-63%	30	19	-36%
System cost	€/kW	63	28	-55%	30	27	-9%
On board storage cost	€/kgH ²	88	85	-3%	66	65	-1%
On board batteries	€/kWh	343	346	1%	246	245	0%
Maintenance cost	€/yr	418	271	-35%	263	204	-22%
Fuel input	kgr/100km	0.58	0.46	-20%	0.49	0.40	-17%
Cost of running the vehicle	€ cents /km	54	42	-22%	42	40	-5%

Stationary applications (1-5 Kwe) of fuel cells

	unit	2025			2050		
		Baseline	10x R&D	% change	Baseline	10x R&D	% change
Stack cost	€/kW	392	203	-48%	224	166	-26%
System cost	€/kW	1509	868	-42%	896	799	-11%
Stack lifetime	Years	9	11	25%	10	12	14%
Fixed O&M cost	€/kWyr	72	30	-59%	22	18	-16%
Overall fuel efficiency	%	92	95	3%	94	95	2%
Electrical efficiency	%	34	37	7%	36	38	5%
Thermal efficiency	%	58	58	1%	57	57	-1%
Electricity production cost *	€/MWh	328	218	-34%	140	126	-10%

* the value of heat is subtracted from this figure

Hydrogen delivered cost to

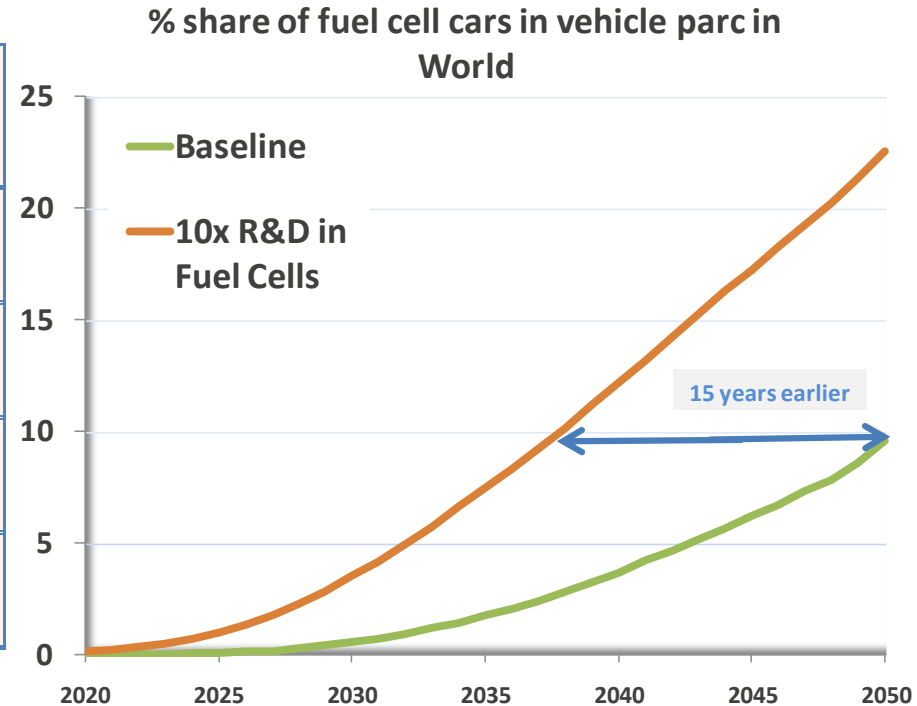
	unit	2025			2050		
		Baseline	10x R&D	% change	Baseline	10x R&D	% change
Industry	€/toe	853	833	-2%	849	839	-1%
Transport	€/toe	1182	1159	-2%	1140	1129	-1%
Residential/commercial	€/toe	1113	1085	-3%	1066	1054	-1%



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R&D scenarios results

Hydrogen penetration index in 2050 (World)	Baseline	No R&D in H2 related techs	10x R&D in Fuel Cells (FC)	10xR&D in H2 production techs
% Share of fuel cell vehicles in vehicles parc	9.6	0.0	22.6	10.2
% Share of H2 ICE vehicles in vehicles parc	4.2	3.1	3.4	4.6
% Share of elec. from fuel cells in final elec. demand *	1.9	0.1	5.0	2.0
% Share in non-electric final demand**	1.4	0.1	3.6	1.5



* Final demand in industry, residential and commercial sectors

** Share of heat and steam from fuel cells in non electric final demand in industry, residential and commercial sectors

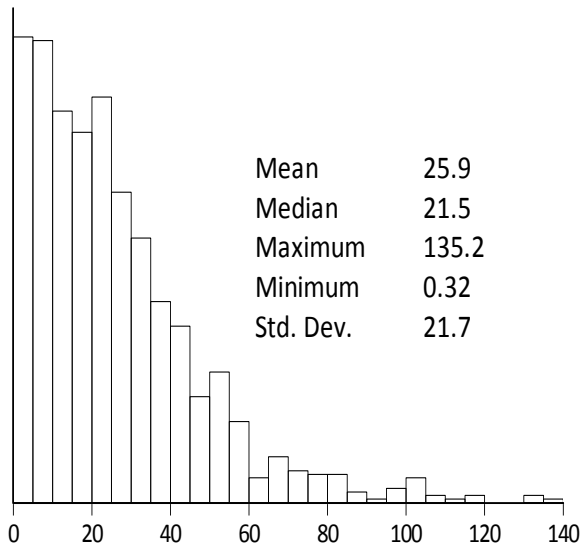


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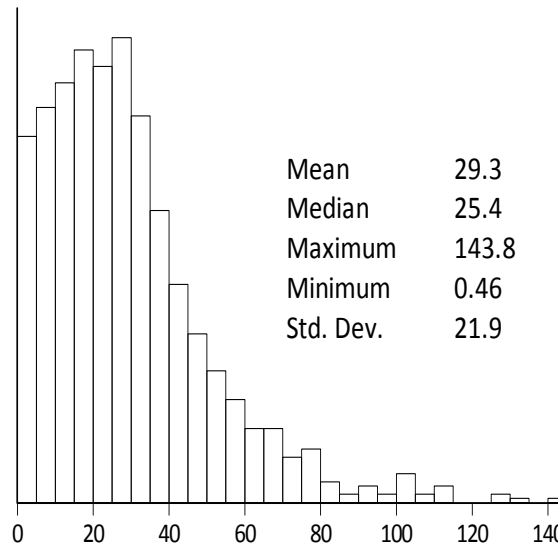
Advanced results from R&D scenarios using the PROMETHEUS stochastic model

Probability distribution of the ratio of discounted* technology sales and R&D expenditures

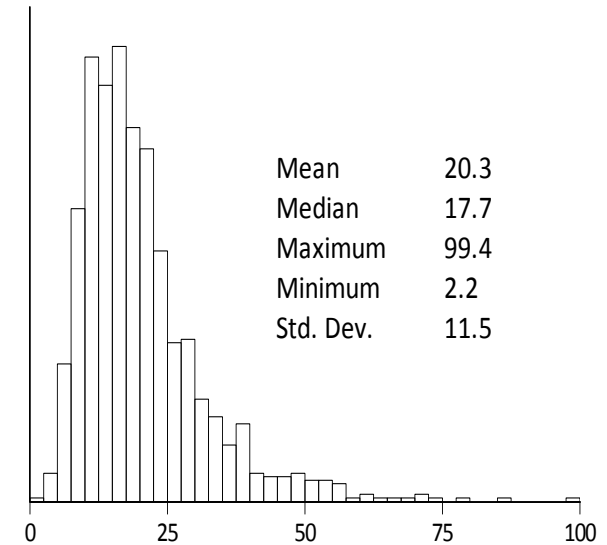
R&D in fuel cells: 1/3 of baseline



Baseline



R&D in fuel cells: 10x Baseline



	1/3 baseline R&D	baseline	10x baseline R&D
Probability to fall below 6	16%	11%	2%
Probability to fall below 10	26%	18%	13%
Probability to exceed 20	53%	61%	40%
Probability to exceed 60	7%	9%	1%

* discount rate: Real interest rate + 6%



- R&D appears to be:
 - Important pre-condition for improvement of H2 related technologies
 - Strong signs of diminishing returns
 - Additional R&D has particularly small impacts on non FC technologies
- Suggestions for R&D scenarios
 - Make R&D infusions massive and early?
 - Discriminate between candidate options?
 - *Don't expect miracles!*



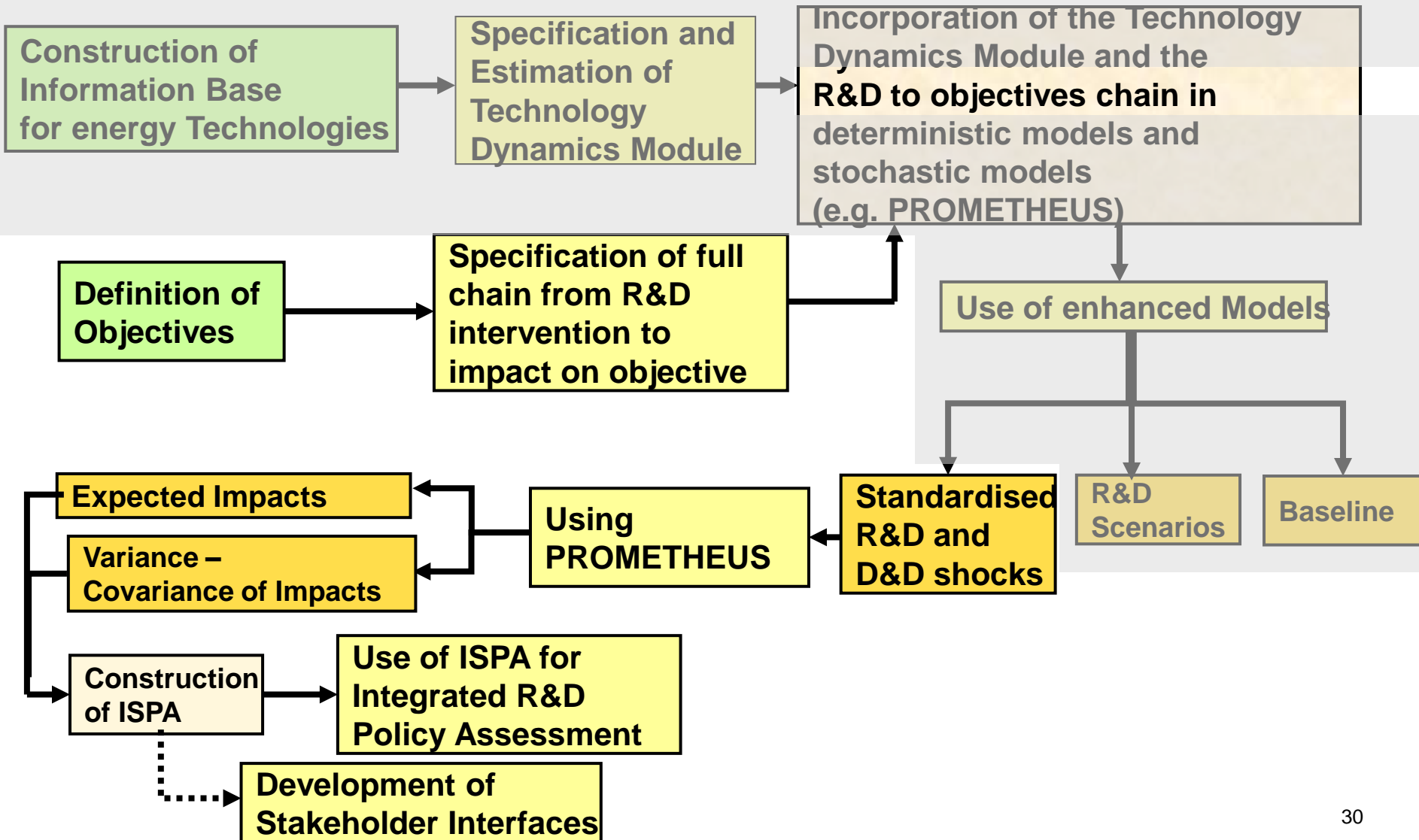
R&D budgeting

- The public R&D policy strategies targeting technological development:
 - Evolve in a context of multiple objectives
 - including both traditional and sustainable development concerns
- They are subject to considerable risk concerning the efficacy of public R&D support to specific technological options



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Using technology dynamics models to build tools for R&D budget exploration





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The ISPA tool

- It is an integrated R&D policy exploration tool, which:
 - Considers multiple objectives
 - Takes into account many technological options as possible candidates for R&D support
 - Places particular emphasis on the **stochastic characteristics** of the impact of R&D actions
- It has been used in the SAPIENTIA project (partly financed by the DG Research of the European Commission)
 - ISPA has been used to perform R&D portfolio exploration providing analytical assessments of the impacts of the 6th FP and input for the initial stages of the elaboration of the 7th



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Objectives considered in ISPA

- **Conventional Objective**
 - Market Impact
- **Global Warming**
 - Temperature Change
- **Ecosystems**
 - Highest temperature increase over a decade
- **Security of Supply**
 - Highest increase in international oil and gas prices in any 3-year period
- **Resource Depletion**
 - R/P ratio of oil and gas
- **Urban Environment**
 - Share of low emission passenger cars
- **European Consumer**
 - Energy cost reduction to consumer
 - Electricity cost reduction to consumer
- **Regional Imbalances**
 - Energy cost reduction to consumer in the Less Developing Countries
 - Electricity cost reduction to consumer in the Less Developing Countries



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Energy technologies considered in ISPA

Classification of technologies	# of options
Classical Thermal	4
Clean Coal	2
Gas Turbines	3
Nuclear	2
Biomass	2
Solar	2
Wind	2
CO ₂ Capture and Seq.	6
Fuel Cells	1
Hydrogen Production	6
Conventional Vehicles	1
Non Conventional Vehicles	1
Other	2
TOTAL	34



Specification of ISPA

- 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 maximized.
 - Subject to the condition that the probability that the other objectives exceed given thresholds is greater than a certain level.
 - Also subject to the budget and non-negativity constraints.



General specification of ISPA

$$\max \Pr \left\{ \sum_j x_j r_{1j}(x_j) > A_1 B \right\}$$

subject to

$$\Pr \left\{ \sum_j x_j r_{ij}(x_j) > A_i B \right\} \geq p_i$$

$$\sum_j x_j \leq B \quad x_j \geq 0$$

where,

$$\bar{r}_i \approx \tilde{N}(\bar{\rho}_i(\bar{x}), V_i(\bar{x}))$$

Where:

- the $x(j)$ are the budget allocations to technology j
- the $r(i,j)$ are random variables representing the impact on objective i of expenditure on technology j
- $A(i)$ are the thresholds for each objective and $p(i)$ the probabilities associated to them
- B is the total R&D budget
- $\bar{\rho}_i(\bar{x})$ and $V_i(\bar{x})$ are the mean and variance covariance of \bar{r}_i and are functions of \bar{x}



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A more concrete ISPA Specification

$$\max_{\mathbf{x}} \frac{\rho'_1(\mathbf{x})\mathbf{x} - A_1 B}{\sqrt{\mathbf{x}'\mathbf{V}_1(\mathbf{x})\mathbf{x}}}$$

, the main objective under consideration

subject to:

$$\rho'_i(\mathbf{x})\mathbf{x} - F^{-1}(p_i)\sqrt{\mathbf{x}'\mathbf{V}_i(\mathbf{x})\mathbf{x}} \geq A_i B$$

, $i=2, \dots, m$ the constraints on the other objectives

$$\mathbf{u}'\mathbf{x} \leq B$$

, the budget constraint

$$\mathbf{x} \geq 0$$

, the non-negativity of budget allocation constraint

$$F(p_i) = \int_{-\infty}^{p_i} 0.39894228 \cdot e^{-0.5z^2} dz$$

, the cumulative standard normal distribution function



Key features of ISPA

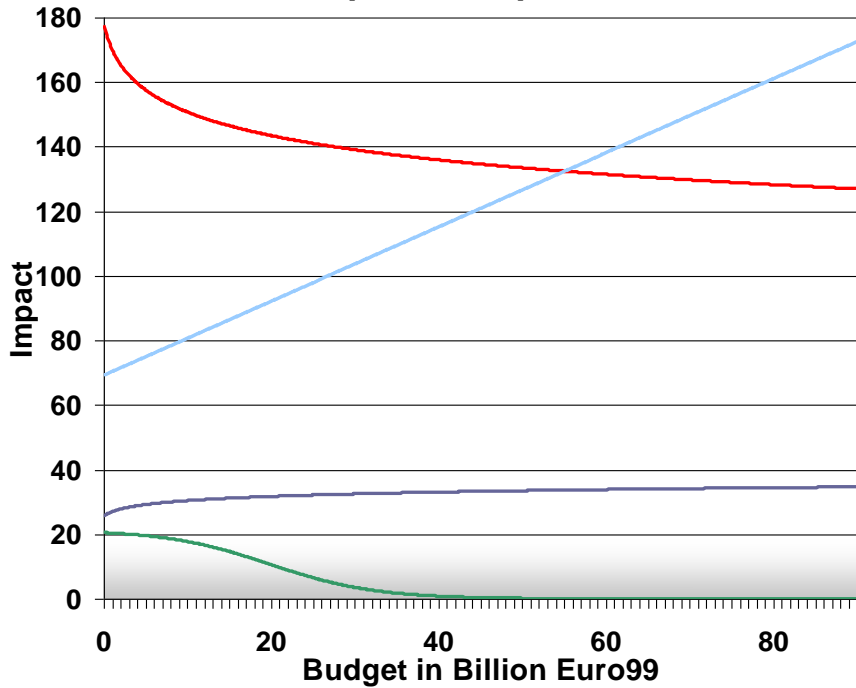
- Single horizon
- It treats the impact of allocation decisions stochastically
 - Possibility to make probabilistic statements
- The allocation itself does not affect the stochastic characteristics of the problem
- The thresholds A_i must be selected to be low enough so as to allow for probabilities p_i greater than 50%.
 - If this condition is not met the problem becomes non-convex and the analysis is altered from “hedging” to “speculation”



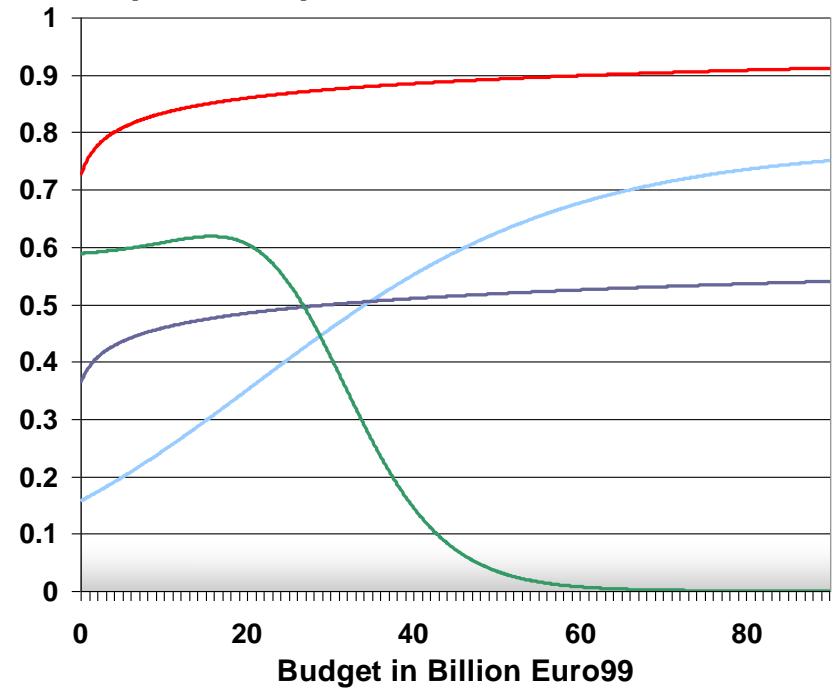
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Change in expectation and standard deviation by increasing the budget

Security of Supply Expected Impact



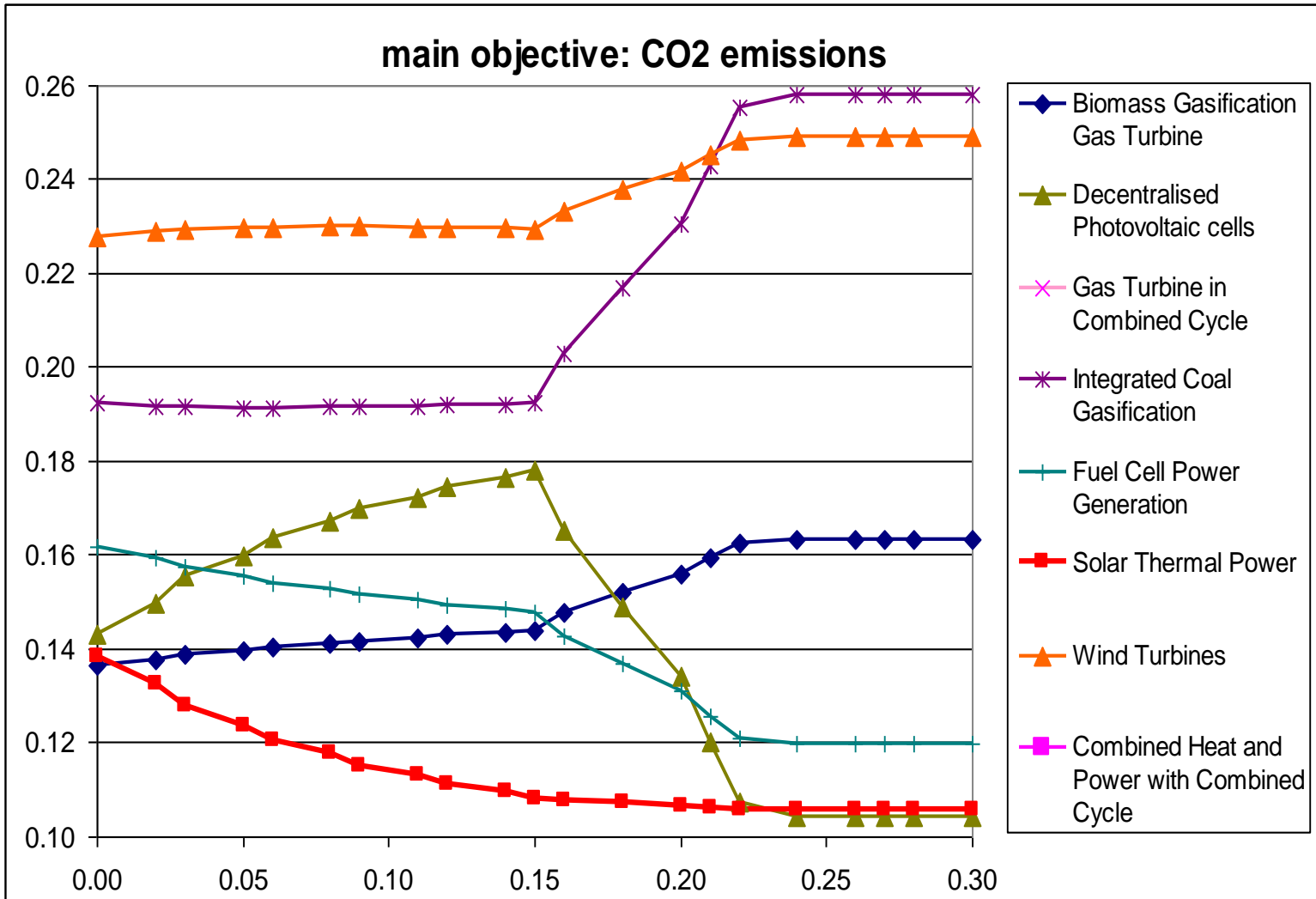
Security of Supply Expected Impact to Standard Deviation



- Electric-Hybrid
- Fuel Cells
- New Nuclear 4th Gen.
- Wind



Solution from ISPA





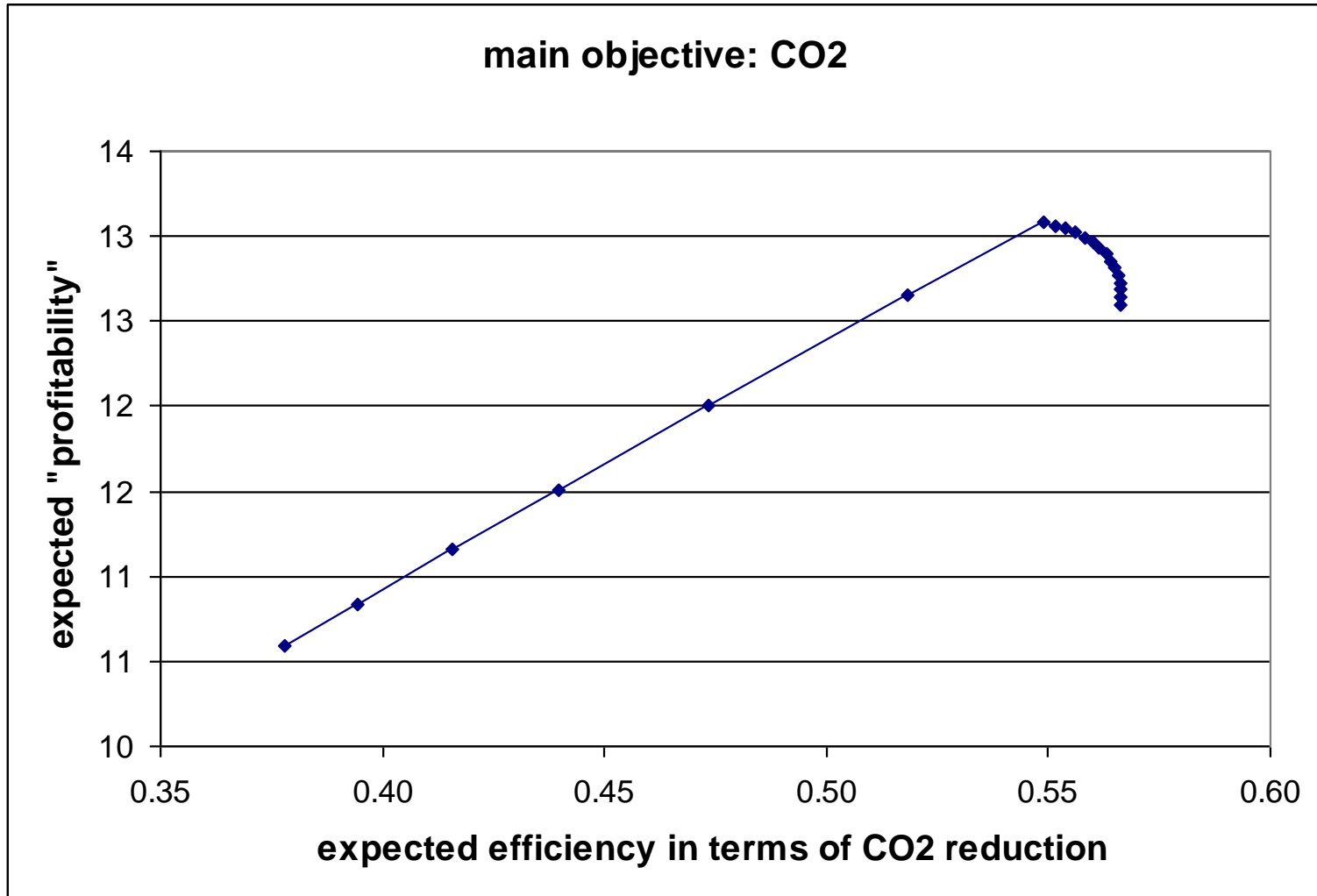
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Integrated Policy Exploration Using ISPA

- Large number of possibilities for policy exploration.
- First a feasible set representing minimum requirements on all the indicators involved must be defined.
- Selected sustainable development indicators can be introduced as principal objectives, allowing the minimum threshold regarding it to be increased and maximising the probability of achieving it.
- This process repeated placing other indicators on the principal objective. Successive solutions lead to the construction of a series of pay-off curves.
- Points of particular interest to policy makers identified along the pay-off surface.
- In the presence of divergent policy mixes, “compromise” solutions could be obtained by using rules and methods developed for multiple criteria optimisation.



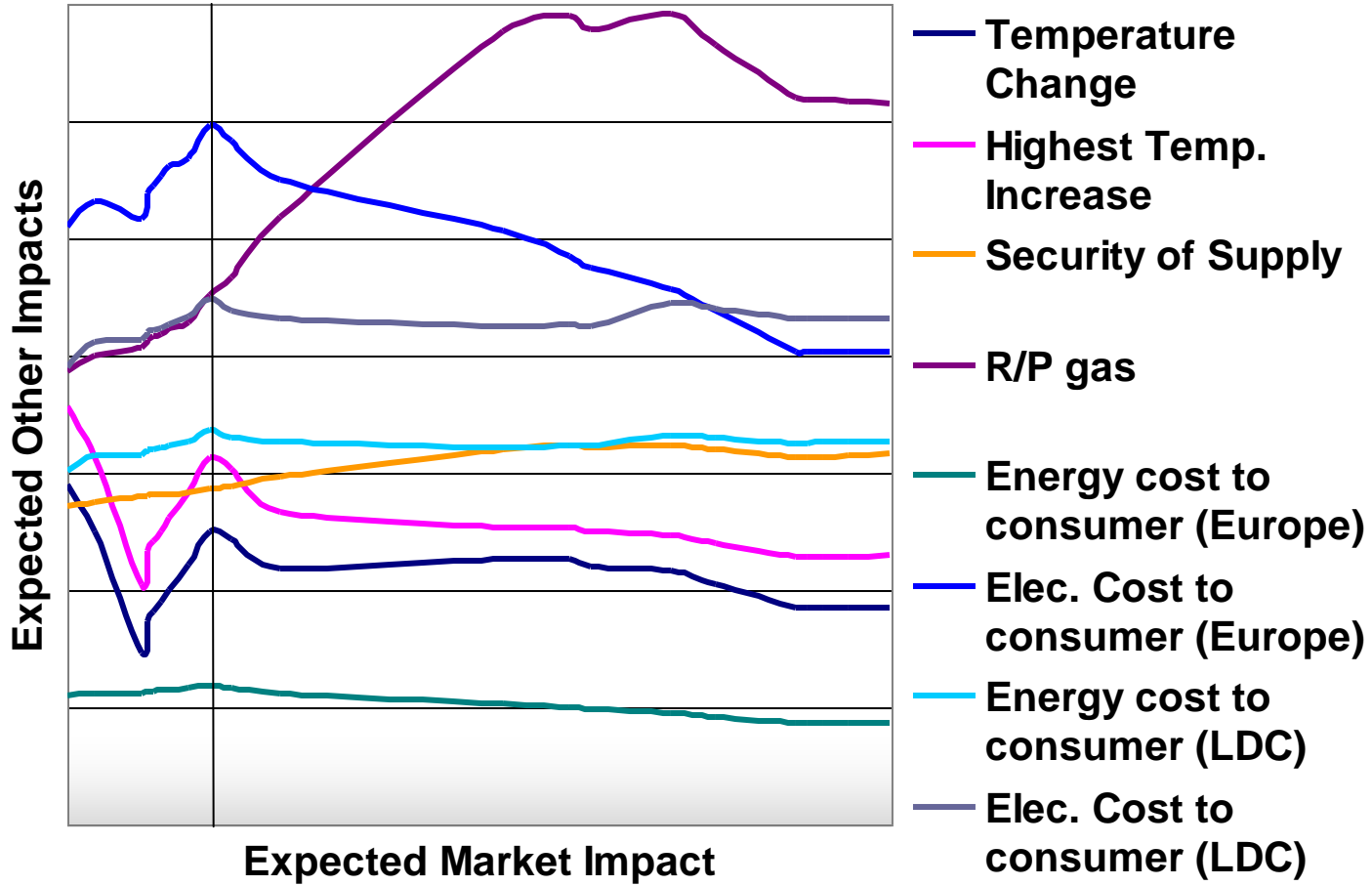
Example of pay-off curve





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Example of pay-off and compromise chosen:





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Exploration procedure adopted

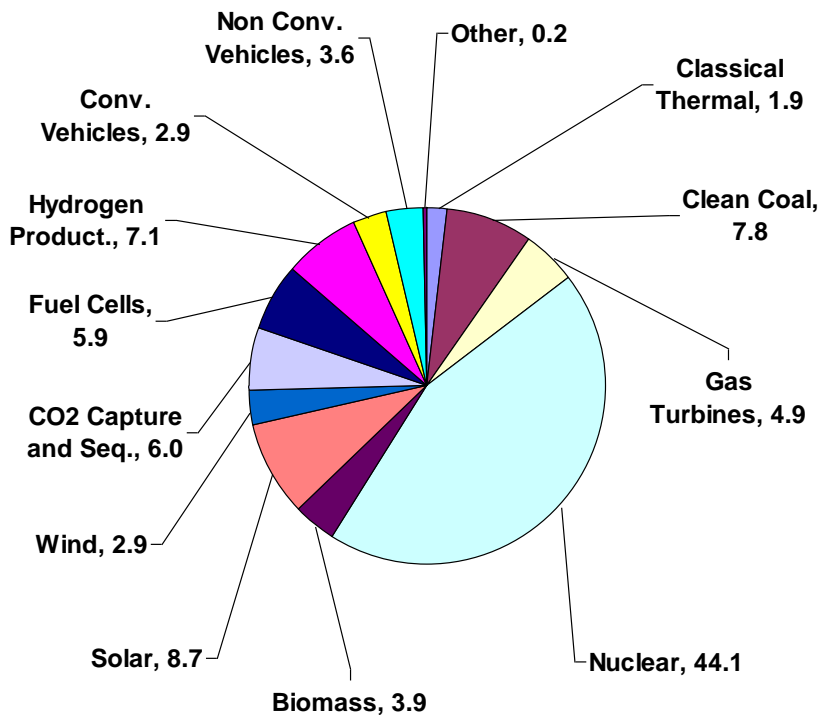
- Starting from existing public R&D budget construct a feasible set exploiting synergies.
- Improving the solution by consolidating synergies and relaxing bounds.
- Improving by sacrificing the probability (or the threshold) requirements for some objectives.
- Guidance for relaxation and sacrificing is provided by shadow costs (dual values).



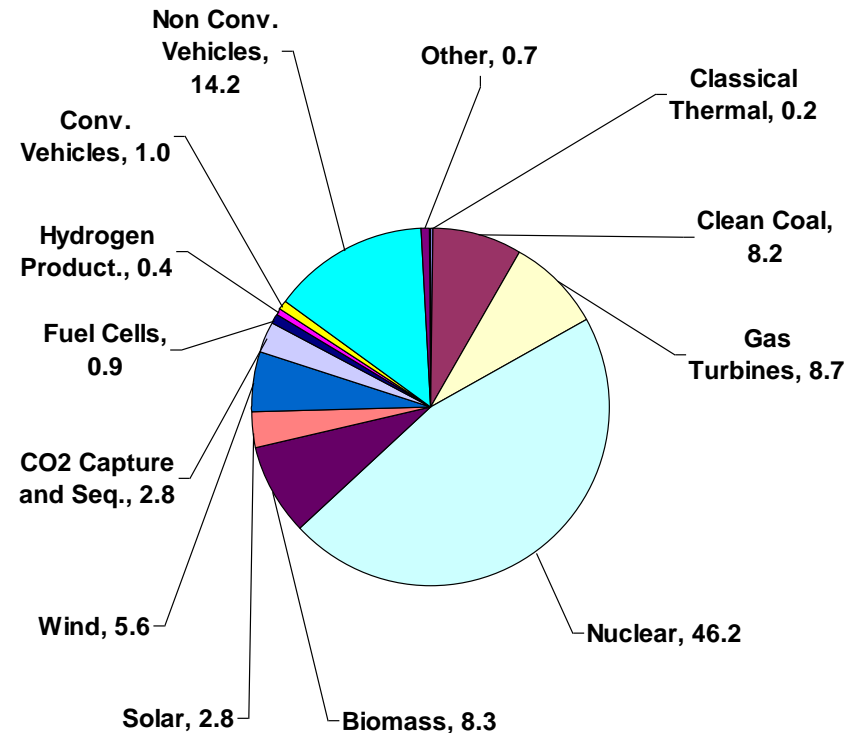
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Comparison of budget shares

Baseline projected GERD
(average 2006-2010)



ISPA derived





General remarks on ISPA

- The methodology has wide potential applications in R&D strategy elaboration and can be extended to cover more technologies (beyond the power generation sector) and encompass a wider range of policy objectives.
- It can be also extended to domains beyond energy R&D policy exploration to address optimal policy exploration in the presence of multiple objectives and uncertain policy impacts.