IEA – Ad Hoc Group on Science and Energy Technologies

Mathematical Tools for Economic Programming Energy Models

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New Links between Basic Research and Applied Energy R&D

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Content

1. Introduction: the tools developed by the IEA
   Energy Technology Systems Analysis Programme

2. Present limits and desirable improvements of
   - underlying theories
   - algorithms
   - expert systems

3. Possible energy R&D strategic objectives

1 – The IEA Energy Technology Systems Analysis Programme (www.etsap.org)

1. Objective
2. Strategy
3. Participants to ETSAP since 1976
4. Achievements:
   - Availability of a group of energy systems analysts
   - Implementation of several economic equilibrium technology explicit models of global, regional, national, local energy systems; and
   - development of systems analysis tools: the MARKAL TIMES model generator (MT)

1.1 – ETSAP's objective

… is to assist decision-makers in the assessment of new energy technologies and policies in meeting the challenges of

- energy needs,
- environmental concerns, and
- economic development,

by carrying out a programme of co-operative energy technology systems analysis.

1.2 – ETSAP's strategy

… in achieving the objectives is twofold.

1. ETSAP has established, and now maintains / enhances the flexibility of consistent multi-country energy / economy / environment analytical tools and capability (the MARKAL TIMES family of models), through a common research programme.

2. ETSAP members also assist and support government officials and decision-makers by applying these tools for energy technology assessment and analyses of other energy and environment related policy issues.

1.3 – ETSAP participants

Australia: ABARE
Belgium: VITO/Uni-Leuven
Canada: NRCan
EC: DG RTD
Finland: TEKES and VTT
Germany: IER/JFZ
Greece: CRES
Italy: ENEA/ENI
Japan: JAERI
Korea: KEMCO/KIER
Netherlands: ECN

Sweden: Uni-Chalmers
Switzerland: PSI
UK: DTI, AEAT
US: BNL/EIA/DOE

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in previous years:
Austria, Denmark, Ireland
New Zealand, Norway,
Spain, Turkey

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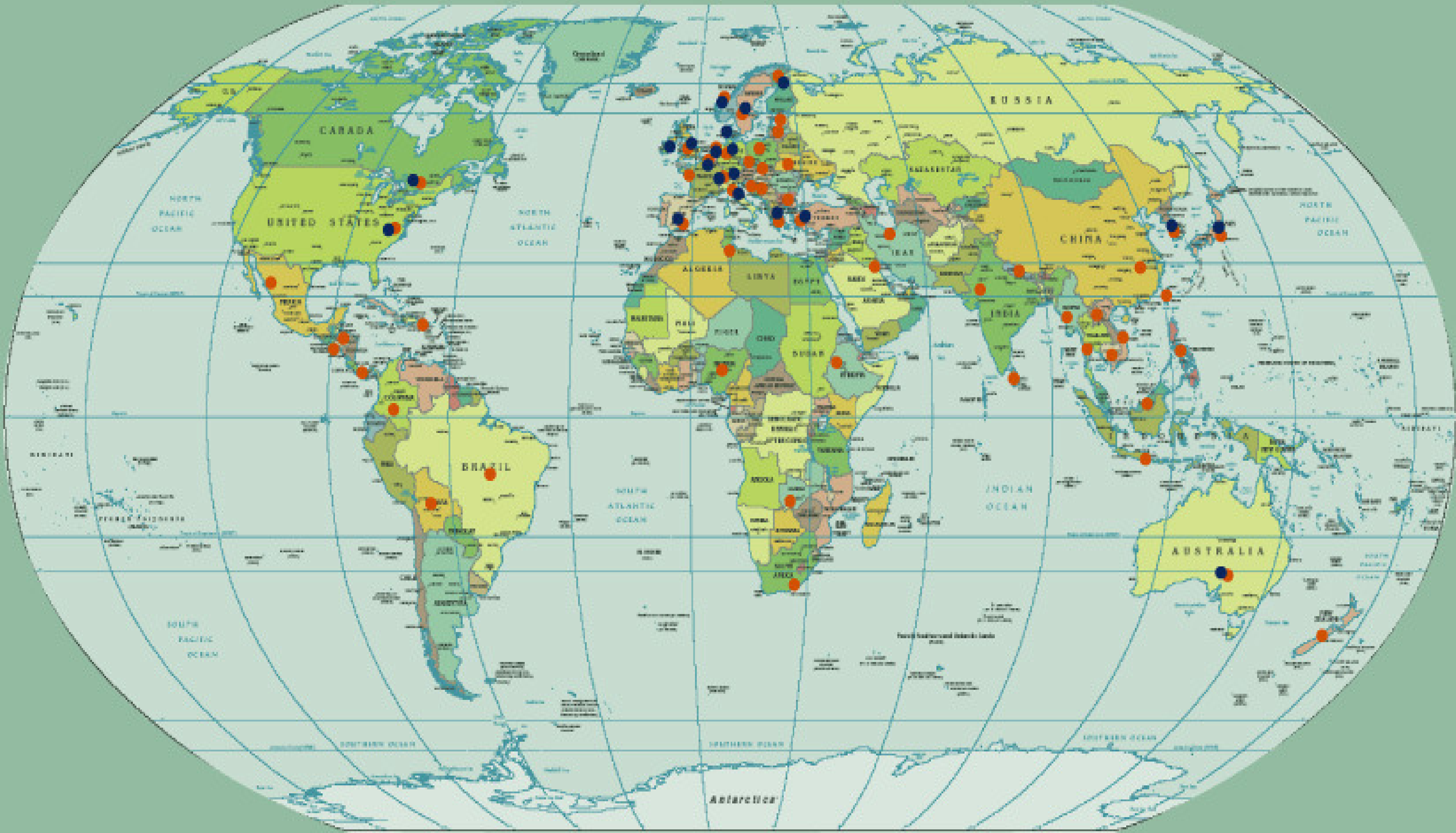
>100 ETSAP tool users (%)

and MARKAL TIMES users across the world



ETSAP Participants

and MARKAL - TIMES users

http://www.etsap.org

1.4 – The MARKAL TIMES model generator

1. From the energy balance of the system to be modelled,
2. By correlating energy to several other data,
3. Each energy market is represented by means of linearised demand supply curves;
4. Assuming framework projections,
5. MARKAL TIMES generates economic equilibrium models,
6. Which are formulated as mathematical programming problems,
7. Making use of structured modelling techniques

1.4.1 – From the Energy Balance of the system

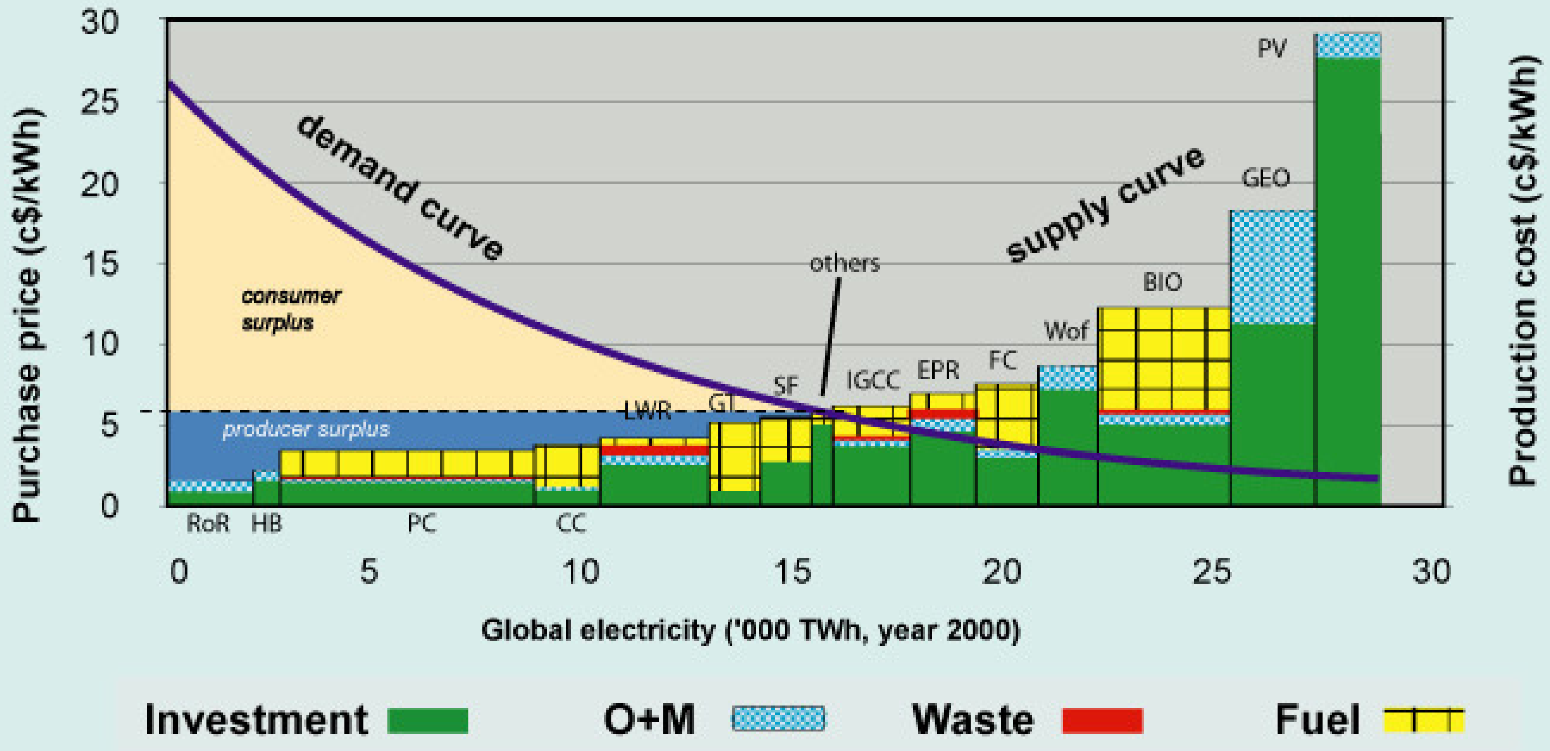
SUPPLY AND CONSUMPTION	Coal	Crude Oil	Petroleum Products	Gas	Nuclear	Hydro	Geotherm. Solar, *etc.*	Combust. Renew.	Electricity	Heat	Total
	Thousand tonnes of oil equivalent										
Production	698779	164131	-	31365	4553	23859	-	215930	-	-	1138617
Imports	1369	60260	28315	-	-	-	-	-	155	-	90098
Exports	-67316	-7550	-11495	-	-	-	-	-	-876	-	-87238
Intl. Marine Bunkers	-	-	-3969	-	-	-	-	-	-	-	-3969
Stock Changes	4526	-1297	-1369	-	-	-	-	-	-	-	1860
TPES	**637358**	**215544**	**11481**	**31365**	**4553**	**23859**	**-**	**215930**	**-722**	**-**	**1139369**
Transfers	-	-	-	-	-	-	-	-	-	-	-
Statistical Differences	13753	-3824	-1989	-3988	-	-	-	-	-	-	3952
Electricity Plants	-290951	-816	-11103	-1344	-4553	-23859	-	-838	126563	-	-206903
Heat Plants	-35986	-123	-4096	-1697	-	-	-	-490	-	36585	-5807
Gas Works	-4670	-	-228	3827	-	-	-	-	-	-	-1072
Petroleum Refineries	-	-204068	201793	-	-	-	-	-	-	-	-2275
Coal Transformation	-45850	-	-	-	-	-	-	-	-	-	-45850
Own Use	-30016	-4422	-15046	-7822	-	-	-	-	-19240	-9335	-85882
Distribution Losses	-126	-	-17	-643	-	-	-	-	-8881	-430	-10097
TFC	**243511**	**2291**	**180795**	**19697**	**-**	**-**	**-**	**214602**	**97720**	**26820**	**785435**
Industry	165870	2092	51984	12449	-	-	-	-	61562	20110	314067
Transport	5280	-	69161	228	-	-	-	-	1307	-	75977
Agriculture	3688	-	16119	-	-	-	-	-	6676	57	32841
Comm. and Publ. Services	5400	-	16014	588	-	-	-	-	6439	450	28892
Residential	43981	-	13652	6431	-	-	-	214602	15817	5581	300064
Non-specified	4174	136	-	-	-	-	-	-	5917	622	10912
Non-energy use	8818	-	13865	-	-	-	-	-	-	-	22683
Electr. Generated - GWh	*1121973*	*-*	*47343*	*5474*	*17472*	*277432*	*-*	*1963*	*-*	*-*	*1471657*
Heat Generated - TJ	*1307224*	*-*	*147659*	*63965*	*-*	*-*	*-*	*13187*	*-*	*-*	*1532035*

Example: China, 2001 (Excluding Hong Kong)

1.4.2 – by correlating energy to other data

1. The energy balance is extended to end users and their demand for energy services
2. Each energy flow is
   - Cross-checked with the stock of existing energy technologies (Reference Energy System)
   - Linked to the emission of various species and
   - Correlated to economic flows and investments
3. Demand and supply curves are built for each market, as illustrated

1.4.3 – each energy market is represented by linearised demand / supply curves



Power plants

RoR = run of the river
HB = hydro basin
PC = pulverized coal
CC = combined cycle
LWR = existing nuclear
GT = gas turbine
SF = steam fossil
others existing
IGCC = int. coal GCC
EPR = new nuclear
FC = fuel cells
Wof = wind offshore
BIO = biomass steam
GEO = geo hot dry
PV = photovoltaic

Typical representation of an energy commodity in MARKAL - TIMES.
The algorithm maximises the global surplus over thousands such markets.

1.4.4 – assuming framework projections

1. Availability of energy resources, by type, region, cost, technology, etc.
2. Economic macro variables by region, year, scenario, etc
3. Environmental constraints by species
4. Technological development, by technology
5. Etc.

1.4.5 – MARKAL TIMES generates partial equilibrium models

Technology explicit and Multi-regional, which assume *Price elastic demands;* and *Competitive markets:* with *Perfect foresight* (resulting in *Marginal value Pricing).*

Underlying principles central to the MARKAL equilibrium are:

- Outputs of a technology are linear functions of its inputs;
- Total economic surplus is max. over the entire horizon,
- Energy markets are competitive, with perfect foresight.

As a result of these assumptions the following properties hold:

- The market price of each commodity is exactly equal to its marginal value in the overall system, and
- Each economic agent maximizes its own profit (or utility).

1.4.6 – formulated as a mathematical programming problem, *composed of*

	a Primal Problem and	a Dual Problem
	Max $c^t x$	Min $b^t y$
s.t.	$Ax \leq b$	$A^t y \geq c$
	$x \geq 0$	$y \geq 0$

where x is a vector of decision variables, $c^t x$ is a linear function representing the objective to maximize, and $Ax \leq b$ is a set of inequality constraints.Each dual variable y_i may be assigned to its corresponding primal constraint.

If the primal problem has a finite, optimal solution x*, then so does the dual problem (y*), and both problems have the same optimal objective value.

The optimal values of the dual variables are also called the shadow prices of the primal constraints. The vector (x*, y*) represents the equilibrium.

1.4.7 – MARKAL TIMES is coded making use of Structured Modelling Techniques

Real size energy system models, with a detailed representation of commodities and technologies, are huge:

- hundreds of thousand of variables and equations, and
- million of coefficients.

How to contain in a feasible size the definition procedures of such huge models?

Instead of being formulated directly by means of decision variables, resource constraints and input parameters, the MARKAL TIMES mathematical programming problem is formulated by means of primitive and compound entities, which are mainly sets (variables, constraints and parameters), indexes and hierarchies.

2 – Present limits, desirable improvements

Improvements are desirable in order to overcome three types of limitations presented by tools.

1. What theoretical framework is necessary to couple the present economic approach with the simulation approach of environment / technological sciences and with decision theories?
2. How to increase the power of solution algorithms and graphic interfaces?
3. How to embed more expert systems characteristics?

2.1 – Theoretical framework

The problem here is to develop mathematically sound theories and tools that can implement the coupling of multi-regional MARKAL-TIMES partial economic equilibrium models with:

1. environment / earth-systems models,
2. general economic equilibrium technology explicit models,
3. possibly in a game theoretic fashion, and with
4. longer term non macroeconomic development drivers.

2.1.1 – Environment / earth system models

Environmental systems are often described by complex non-linear simulation models (SM, e.g. Eulerian models to describe ozone episodes, General Circulation Models to describe climate change). How permit a coherent dialogue between these models?

- Soft-linking: the results of the Simulation Model are fed into the MARKAL TIMES model, it finds a new socio-economic equilibrium, and the new emission profiles are fed back into the simulation model, till both solutions converge.
- Simplified hard-linking: a reduced subset of one model is inserted into the full size other model, without changing the method.
- Coherent dialogue: The basic idea is to use MARKAL TIMES as an "oracle" and the Simulation Model as another oracle; both of them send information to a master program, which queries the oracles in order to converge to an optimal configuration.

2.1.2 – General economic equilibrium technology explicit models

Is it possible to extend the MARKAL TIMES approach – technology rich, clairvoyant and based upon the substitution of alternatives – to represent the full economy of the system, and its development in a closed way, as in Computable General Equilibrium models?

- Soft-linking: MT provides Marginal Abatement Costs to the CGEM and the CGEM feedbacks a new general economic framework.
- Hard-linking: to extend to several production functions the present simplified MARKAL-MACRO approach, where the whole economy is represented by just one Production Function.
- Closed I/O framework: by making use of Von Neumann rectangular I/O matrixes – where every sector has more than one producer and each producer can deliver more than one commodity – and improving the equilibrium concept from the static to the dynamic dimension and to allocate investments.

2.1.3 – In a game theoretic fashion

Recent multi-regional MARKAL TIMES models calculate cooperative forms of equilibria. Some game theoretic reasoning should be involved when one looks at the geopolitical consequences of major changes in the economy (e.g. oil, climate, etc.).

- In a first experiment to use MT models in a non-cooperative game on carbon emissions abatement, the damage cost is expressed as linear function of cumulated emissions and this gives rise to simplistic Nash equilibrium solutions.
- If we have non-linear cost functions associated with carbon concentrations, the Nash equilibria will be much more difficult to compute. Under some simplifying assumptions it should still be possible to formulate an overarching "non-cooperative" game, involving the strategic decisions of regional carbon abatement, with a Nash equilibrium solution obtained via the solution of variational inequalities.

2.1.4 – Longer term development drivers

Economic values calculated by MARKAL TIMES models at equilibrium are expressed in present real term monetary units (the “numeraire”). Prices in years far away from the present are difficult to compare with present prices.

Is it possible to use alternative “units” to measure producers profits and consumers utility? Since the equilibrium points result from the interplay between supply curves (mainly technology and resource driven) and demand curves (eventually driven by the social propensity to consume), it would be interesting to study variants of MT models based upon different “numeraires”, either socially oriented (e.g. population, labour force) or technology oriented (long term technological progress, innovation cycles).

2.2 – Algorithms

The analyses would benefit from the availability of new / improved algorithms for:

1. Quicker solutions of non linear programming problems;
2. Increasing the choice possibilities of efficient huge LP solvers; and
3. More stable solutions of linear problems with huge dimensions: approaching one million equations / variables and ten million matrix coefficients;
4. Laying out automatically in a more compact graphical form the Reference Energy System.

2.2.1 – Quicker non linear programs solvers

Several variants of MARKAL TIMES models, i.e.

- The general equilibrium version, MARKAL-MACRO
- The version that internalises some externalities (DAMAGE)
- The Endogenous Technology Learning (ETL), etc.

use a non linear objective function, or some non linear constraints, or both. However, analysts tend to avoid these more powerful formulations for practical reasons, because the solution times of non linear variants is normally an order of magnitude or more greater than the equivalent linear problem (e.g.: 10 hours instead of one hour).

It would be useful to have more and more powerful non linear solvers.

2.2.2 – More choice of efficient solvers

Recent multi-regional global MT models are huge: about half a million equations, half a million variables and ten million matrix coefficients).

Solvers available as freeware or shareware cannot even cope with the dimension of the problem, or if they do, they cannot converge to feasible / optimal solutions.

Commercially available solvers have a great spread in cost and performance: the cheapest ones, if they arrive to a solution, may require 20 or more times as compared to the fastest ones.

More choice of the fastest solvers might avoid monopolies, reduce prices (recently up to 9000$ per licence) and make the tools (more readily) available across the world.

2.2.3 – More stable solutions of huge LP

Recent multi-regional global MT models are huge: about half a million equations, half a million variables and ten million matrix coefficients or more. When these dimensions are approached, the theorem of uniqueness seems to evaporate due to numerical instabilities.

While global indicators and values are stable to the last few significant digits, solution values of non degenerate decision variables and shadow prices are significantly different, depending on the solver, the solution algorithm and the starting point.

Theoretical studies and experiments on the numerical stability of large scale LP can identify conditions for more reliable solutions.

2.2.4 - Compact graphical layout of RES

In the technical economic modelling approach underlying MT models, the inter-connection of commodity markets and technologies is called Reference Energy System (RES).

The graphical representation of the RES is essential to understand

- if the model responds to the type of analysis required,
- where are the bottlenecks of markets / technologies;
- what branches / chains are too specific or to generic compared to the “value” of the corresponding sector;

It would be of great help to analysts the availability of algorithms capable of compacting the RES and drawing it in an ordered and contained form, without the need of spending days in drawing it manually or patching hundreds of sheets to the walls.

2.3 – Expert systems

One way to improve the quality of the analyses and to spread their use is to embody in ETSAP tools some *expert system* capabilities. This can include procedures capable of:

1. relating more directly MARKAL TIMES models to decision makers questions (decision support systems);
2. making possible the cooperation of different teams to build and analyse the same model (multi-tasking); and
3. tracing back from any equilibrium solution value to the subset of input data explaining it.

2.3.1 – Decision support systems: input

The objective is to construct models tailor-made to decision makers questions. Procedures have to be developed capable of:

- Adding to the tools the set of policy relevant questions (what is the cost of producing 20% of TPES out of new renewables; what is the effect of adding a subsidy to …);
- Identifying market and technologies more relevant to each question;
- Asking the appropriate input data for translating each question in quantitative elements;
- generating the additional decision variable, resource constraints, scenarios appropriate to the questions

2.3.2 – Decision support systems: output

The aim is to simplify the transformation of the numerical model results into answer to decision makers. Although the reporting chain has been recently hugely improved, it would help to add:

- modules connecting the each decision maker question to the results where answers are provided;
- Procedures to help the user exploring the robustness of the answers;
- Procedures to provide the significance of each question / answer in explaining the behaviour of the system and its development.

2.3.3 – Networking different expertise

In theory a single person can develop and analyse the model of a simple energy system.

In most cases however it helps to make interdisciplinary teams work together, each contributing diversified pieces of knowledge.

The goal is to implement a framework that combines Web technologies, Data Base Management Systems and object oriented programming with ETSAP tools in order to develop and exploit the same model at distant locations.

2.3.4 – Backwards sensitivity analyses

The problem is to build "expert procedures" capable of tracing back from an equilibrium solution the subset of input data explaining specific solution values.

The starting point is provided by some post-optimal direct sensitivity analyses (what changes in the solution when an input element changes?)

The question of the backward sensitivity analysis is: what input changes are necessary to achieve a desired result?

- Value flows: what sets/elements drive the most significant economic values of the system and its development?
- Causality flows: what input determines a result?

3 – Possible energy R&D strategic goals

After listing some “mathematical” improvements as desirable for ETSAP, let me conclude by contributing with some analogies and personal ideas to the core strategy of the Ad Hoc Group on Science and Energy Technologies (AHGSET), which is to identify “basic science breakthroughs required to meet world energy challenges (demand pull)”.

Major topic of concern for sustainability are climate change, security of the energy services and energy productivity. In these same sectors, what development opportunity would be possible if more R&D funds and resources?

3.1 – Climate change

Since it exists, the earth climate depends on events out of reach for the inhabitants of the earth.

Since the industrial revolution started, the amount of greenhouse emitted is changing the climate equilibrium.

The success of the human breed has triggered an uncontrolled experiment on the climate.

Is it thinkable / possible to master the global energy system to such a degree that it becomes the regulator of the earth climate, switching from the present uncontrolled climate change experiment to a controlled one?

3.2 – Security of energy services

Delivering to end-users the energy services they need is a major concern of governments across the world. Looking beyond the present (heavy) concerns on oil supply, energy infrastructures and price instabilities, what is the long term strategy of paradigm we are looking for?

Can we achieve in 2-3 generations what has been achieved in hundreds of generations by the food chain, which

- Is available accessible and affordable globally, at the source;
- Supplies a large variety of inter-substitutable options;
- Offers an immense choice to the final consumers,
- At different level of elaborations, etc.

3.3 – Energy productivity

In the last fifty years, the productivity of the economic factors at large have increased much more than the energy productivity. How is it possible to increase it substantially in the future?

Other mature sectors have enjoyed an unexpected increase in productivity. For instance the telephone sector, a century after the discovery, is in transition from fixed network infrastructures to wireless systems and cell phones. Some developing country may enjoy of this more productive system without the need to build the old wire network.

Is it thinkable / possible to repeat for energy the improvement experienced by the telephone sector?

3.4 – The present gap: energy R&D funds

Global values (year 2000, in BUS$)		% GDP
Economic resources	about 70000	
GDP	35000	
Primary energy (TPES)	1400-1800	4-5%
Final energy (TFC)	3000-3500	10%
Useful energy (UE)	about 10000	30%
Total R&D funding	about 600	1.7%
	(EU Lisbon objective 2010	*3%)*
Energy R&D	about 10	

(1.7% of total R&D, and 0.3% of energy sales)