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Introduction to ETSAP and the
MARKAL-TIMES models generators
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Program of Energy Technology Systems Analysis

Network of Expertise in Energy Technology
Of the International Energy Agency – IEA, Paris

Content

A – What is Energy (Technology) Systems Analysis?
B – Where in the analyses IEA/ETSAP contributes?
C – Achievements: models and projects based upon
ETSAP tools (the MARKAL and TIMES model
generators, the ANSWER and VEDA users’ interfaces)
D – Challenges ahead
E – Advantages of joining ETSAP
F – What is the Programme for Energy Technology
Systems Analysis of the International Energy Agency?
**A1 – Technology Systems**

An energy technology is any device that produces, transforms, transmit, distribute or uses energy, such as refineries, power plants, pipelines, boilers, trucks, lamps, kilns, ovens, etc.

None of them works in isolation, all together they form a system.

As for economic goods, some technologies are complementary: I cannot heat my apartment with natural gas if it is not extracted, purified, transported and distributed. If the transport technology becomes cheaper, more gas heating systems will be used.

Other technologies are substitute: coal fired and nuclear power plants, an compact fluorescence and a incandescence lamp. If the first cost less, the latter has a smaller market.

**A2 – Systems Analysis**

Systems analysis “applies systems principles to aid decision makers in problems of

a. identifying,

b. quantifying, and

c. controlling

a system” (quoted from Principia Cybernetica). “While taking into account multiple objectives, constraints, resources, it aims to specify possible course of action, together with their risks, costs and benefits.”

Since energy systems are large and complex analyses are supported by models, which are formal (mathematical) representations of the system.
A2a – Identification of the system

a. Space boundaries: the globe, region, nation, province, town; single or multi-region;

b. Logical boundaries: from mining to the production of useful energy and energy services;


d. Components: energy commodity flows (natural gas, coke, gasoline, etc.), transformation technologies (power plants, refineries, etc.) and demand devices (car, fridge, etc.); and

e. Connections and Dependencies.

A2b – Quantification of the present system

Four main dimensions are quantified:

a. Energy commodity flows

b. Stock of existing transformation processes and end use devices, by category and vintage

c. Technology costs, commodity prices, total system value

d. Emissions by species

e. The economic ‘rationale’ of the systems is reconstructed
   1. by Commodity: quantities and prices are the equilibrium point of step-wise supply – demand curves;
   2. by Technology: the stock results from ranking available options through dynamic economic cost – benefit analyses
### A2b1 – Quantification of energy flows

#### Thousand tonnes of oil equivalent

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<th>SUPPLY AND CONSUMPTION</th>
<th>Coal</th>
<th>Crude Oil</th>
<th>Petroleum Products</th>
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<th>Nuclear</th>
<th>Hydro</th>
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</table>

Example: China, 2001 (Excluding Hong Kong)

### A2b2 – Characterization of the existing stock of energy technologies and end-use devices

#### General Technology Economic Environmental Labour & Mat. Ref.

**Technology**
- **Av. size**
- **Currency**
- **GHG emissions**
- **Materials**
- **Title**

**Tech. sector**
- **Existing capacity**
- **Costs**
- **Solid waste**
- **Steel**
- **Author**

**Data quality**
- **Construction time**
- **Investment**
- **Liquid waste**
- **Concrete**
- **Editor**

**Technical availability**
- **Technical life**
- **Fixed & O&M**
- **Gaseous waste**
- **...**
- **Type**

**Commercial availability**
- **Max. capacity**
- **Variable & O&M**
- **Acoustic impact**
- **...**
- **Year**

**Prototype**
- **Av. Availability**
- **Fuel**
- **Land use**
- **Labour**
- **Access**

**Commercialization**
- **Energy/input**
- **Total ex. fuel**
- **Construction**
- **...**
- **Operation**

**Market share**
- **Energy/output**
- **Total ind. fuel**
- **Operation**
- **...**
- **Commiss.**

<table>
<thead>
<tr>
<th>Country</th>
<th>Heavy Fuel Oil for Industry (BP)</th>
<th>Light Fuel Oil for Households (US05/1L)</th>
<th>Automotive Diesel Oil (BP)</th>
<th>Unleaded Premium (BP)</th>
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</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>387.63 L</td>
<td>0.708 L</td>
<td>0.822 L</td>
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<td>Slovak Republic</td>
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<td>1.255 L</td>
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<td>United States</td>
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<td>2.466 L</td>
<td>2.824 L</td>
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</tr>
</tbody>
</table>

A2b4 – Emissions by species and process

**Emissions in kilotonnes, except CO2 in megatonnes**

<table>
<thead>
<tr>
<th>Soap/WT Code</th>
<th>Description</th>
<th>NOₓ</th>
<th>NO₂</th>
<th>NO₃</th>
<th>NOₓ⁺H₂O</th>
<th>CO₂</th>
<th>CO</th>
<th>CH₄</th>
<th>N₂O</th>
<th>NH₃</th>
</tr>
</thead>
</table>

**GROUP 1: PUBLIC POWER, COGENERATION AND DISTRICT HEATING**

- **16106:** Public power and cogeneration plants
  - **161061:** Emissions from plants = ~300 MW
    - NOₓ: 1.1 Gt
    - NO₂: 0.3 Gt
    - NOₓ⁺H₂O: 0.3 Gt
    - CO₂: 3.0 Gt
    - CO: 0.1 Gt
    - CH₄: 0.1 Gt
    - N₂O: 0.0 Gt
    - NH₃: 0.0 Gt

**GROUP 2: INDUSTRIAL**

- **16203:** Industrial plants = ~500 MW
  - NOₓ: 2.5 Gt
  - NO₂: 0.5 Gt
  - NOₓ⁺H₂O: 0.4 Gt
  - CO₂: 7.0 Gt
  - CO: 0.2 Gt
  - CH₄: 0.2 Gt
  - N₂O: 0.0 Gt
  - NH₃: 0.0 Gt

**GROUP 3: TRANSPORT**

- **16301:** Transport vehicles = ~150 MPV
  - NOₓ: 0.5 Gt
  - NO₂: 0.1 Gt
  - NOₓ⁺H₂O: 0.1 Gt
  - CO₂: 1.5 Gt
  - CO: 0.0 Gt
  - CH₄: 0.0 Gt
  - N₂O: 0.0 Gt
  - NH₃: 0.0 Gt

**GROUP 4: RESIDENTIAL AND COMMERCIAL**

- **16402:** Residential and commercial buildings
  - NOₓ: 0.2 Gt
  - NO₂: 0.0 Gt
  - NOₓ⁺H₂O: 0.0 Gt
  - CO₂: 0.4 Gt
  - CO: 0.0 Gt
  - CH₄: 0.0 Gt
  - N₂O: 0.0 Gt
  - NH₃: 0.0 Gt

**GROUP 5: OTHER**

- **16504:** Other sources
  - NOₓ: 0.1 Gt
  - NO₂: 0.0 Gt
  - NOₓ⁺H₂O: 0.0 Gt
  - CO₂: 0.0 Gt
  - CO: 0.0 Gt
  - CH₄: 0.0 Gt
  - N₂O: 0.0 Gt
  - NH₃: 0.0 Gt

(Note: SO₂ emissions are not included in the table.)
**A2c – Control of system’s future developments**

1. Policy makers define the targets
2. Analysts calculate possible development paths of the system (energy fuels and technologies, costs and emissions)
3. From a menu of “control” tools offered by political sciences, analysts identify optimal control strategies for each target, evaluate their impacts and tradeoffs between diverging objectives / dimensions
4. Decision makers adopt a strategy or ask for more analyses or define alternative targets

ETSAP has developed an innovative methodology and tools for carrying out steps 2 and 3 through models

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**B – Where the Energy Technology Systems Analysis Program of the IEA contributes?**

1. Identification and representation of Reference Energy Systems
2. Integration of the four main quantitative dimensions of the problem: energy, engineering, economy and environment
3. Representation of the systems and their developments in technical economic equilibrium models (MARKAL – TIMES models generators; ANSWER – VEDA users’ interfaces)
4. Generation of development paths of energy system flows, technologies, costs and emissions (scenarios)
5. Evaluation of the energy, technological, economic and environment impact of different policy objective and control strategies to be adopted, under uncertainty.
**B1 – Reference Energy System**

![Diagram of energy system](image)

**B2a – Energy prices as equilibrium point of technical-economic (inverse) supply-demand curves**

![Graph of energy prices](image)

Power plants:
- RuR = run of the river
- HB = hydro-basin
- PC = pulverized coal
- CC = combined cycle
- LWR = existing nuclear
- GT = gas turbine
- SF = steam fossil
- others existing: OGDCC = on-grid coal OGC
- EPR = new nuclear
- FC = fuel cells
- WD = wind offshore
- BI = biomass steam
- SEO = gas hot dry
- PV = photovoltaic

Typical representation of an energy commodity in MARKAL - TIMES. The algorithm maximises the global surplus over thousands such markets.
**B2b – The unit price of emissions as equilibrium point of supply – demand curves**

Emissions / wastes (i.e. commodities with negative values) are specified in terms of avoided emissions / wastes, where:

- **Q** = emission reduction;
- The (inverse) supply curve (Q) = the cost of emission reduction technologies and options (the ‘cost’ is zero when reductions are not taking place, it increases when alternative less polluting technologies are used); and
- The (inverse) demand curve (Q) = the damage function of actual emissions (the ‘cost’ is maximum when the emission is not reduced and decreases when reductions increase).

The unit (marginal) value of the emission is given by crossing point of the two curves at the economic equilibrium.

**B3 – ETSAP tools ...**

a. … are based upon a commercial language (Generalized Algebraic Modelling System, GAMS) and commercial Linear and Non Linear Programming problems solvers.

b. ETSAP has developed (and distributes free of charge) MARKAL and TIMES: two high level computer codes that generate technical-economic models of energy-environment systems.

c. ETSAP related companies have developed ANSWER and VEDA, two user-friendly commercial interfaces for data input and result reporting.

d. Users have developed, and continue to develop hundred of models assembling a data base per model.
**B3a – Base assumptions of MARKAL-TIMES**

Underlying principles central to the MARKAL-TIMES equilibria are:

- Outputs of a technology are linear functions of its inputs;
- Total economic surplus (or total utility) is maximised over the entire horizon (or total system cost is minimised);
- Energy markets are competitive, with perfect foresight (both cases with exceptions, see variants).

As a result of the 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).

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**B3b–Formulation as math. programming problems**

Composed of: a Primal Problem and a Dual Problem

\[
\begin{align*}
\text{Max } & \quad c^\prime x \\
\text{s.t.} & \quad A x \leq b \\
\end{align*}
\]

\[
\begin{align*}
\text{Min } & \quad b^\prime y \\
\text{s.t.} & \quad A^\prime y \geq c \\
\end{align*}
\]

where:

- \( x \) is a vector of decision variables,
- \( c^\prime x \) is a linear function representing the objective to maximize, and
- \( A x \leq b \) is a set of inequality constraints.

Each dual variable \( y \) may be assigned to its corresp. primal constraint.

If the primal problem has a finite, optimal solution \( x^* \), then so does the dual problem \( (y^*) \); both problems have the same optimal obj. 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.
**B3c – Different levels of economic ‘rationale’**

In principle there are 3 modes of building scenarios with MARKAL-TIMES models, depending on the scope of the system that participates to implementing policies:

1. The least cost version (Standard MARKAL) evaluates the impact on the energy sectors, including the end-use devices;
2. The partial equilibrium version (MARKAL-ED; MARKAL-MICRO) includes in the evaluation the effects on the consumption levels;
3. The general equilibrium version (MARKAL-MACRO) evaluates the effects on the whole economy.

Any mode is compatible with any additional policy constraint (on emissions, energy dependence, efficiency, ...)

**B4 – Technology are ranked according to dynamic economic cost-benefit analyses**

Economic equilibrium conditions determine what technologies are competitive, marginal or uncompetitive in each market. The evolution of investment costs, operation and maintenance costs, technical efficiencies and lifetime of each technology, together with the evolution of input and output energy commodity prices, determine changing cost-benefit conditions over time.

In a system view, where all energy commodities (flows and services) as well as all energy technologies are interlinked, the benefit-cost ratio provides a ranking indicator of energy supply technologies and end-use devices on a 'level playing field'.
B5 – Evaluation of policies with ETSAP tools

ETSAP tools are typically used to evaluate policy options in the following fields:

a. Technology assessment
b. Impact of energy related options
c. Environment and emission options assessment

B5a – Typical applications of MARKAL-TIMES: technological assessment

• Analysis of competitiveness of technologies or energy chains (gas or district heating grid?) under different economic assumptions and market barrier removal
• Assesses bundles of competing and/or of complementary technologies, rather than stand-alone evaluations
• Impact of Technological Progress and Aids to Research, Development, and Deployment (learning by doing, learning by researching)
• Cost-curves (several types)
• Life-cycle analysis in a dynamic setting (cradle-to-grave)
**B5b – Typical applications of MARKAL-TIMES: impact evaluation of energy related options**

- Mandatory micro-measures in each sector: building code, building retrofit programs, modal-split incentives in freight and passenger transports, energy efficiency programs, etc. vehicle standards
- Energy taxes, investment subsidies (green and white certificates; clean/ efficient technologies);
- Energy security evaluation E.g. Measured by oil/ gas/ nuclear fuel imports Energy Options evaluation
- Education, information
- Social constraints: e.g. nuclear

**B5c – Typical applications of MARKAL-TIMES: environment and emission options assessment**

- Emission taxes, incentives to non polluters; tax redistribution issues.
- Emission Cap-and-trade systems: global or partial coverage, multiple bubbles, etc.
- Hybrid system: caps + ceiling on emission price.
- Emission intensity standards and regulations.
- Effects of internalising environmental externalities.
- Alternative allocations of emission rights to regions, sectors. Lumped allocations versus output-based allocations.
- Energy intensive materials & urban solid waste management
C – Achievements: models and projects based upon MARKAL-TIMES

ETSAP experts have developed at different scale:

1. global,
2. regional,
3. national, and
4. local models, and
5. participate to national and international projects.

[Each model is a set of data files, which fully describes the underlying energy system (technologies, commodities, resources, demands for energy services, general parameters) in a format compatible with the associated model generator (MARKAL or TIMES). Each set of spreadsheets (.xls) or databases (.mdb) defines one model (perhaps consisting of several regions) and is “owned” by the developer(s).]

C1 – Global multi-regional models

• The IEA/ETO uses a MARKAL model in the analysis of Energy Technology Perspectives (ETP), feasible substitution options and sustainable alternatives.
• The US-EIA uses the System for Analysis of Global Energy markets (SAGE, a myopic version of MARKAL) to explore possible developments of international energy markets.
• The European Fusion Development Agreement uses a TIMES model for assessing the potential of fusion plants.
• With the TIMES Integrated Assessment Model (TIAM, stochastic), ETSAP contributes to the study No.22 of the Energy Modeling Forum “Climate Policy Scenarios for Stabilization and in Transition” for “Hedging Strategies” and “Transition Scenarios”.
• The Paul Scherrer Institute (CH) uses a Global MARKAL-Macro model with endogenous learning to study the interaction between mitigation and innovation diffusion.
C2—Example of regional models for policy analyses

- Ranking new technologies for an energy RD&D group strategy of the main IEA countries (10 countries, MARKAL, IEA)
- Inter-provincial cooperation, emission permits and energy trading among the Canadian provinces (14 region, MARKAL)
- The Northeast States for Coordinated Air Use Management (US-NESCAUM) assesses Clean Air Act goals (9-state MARKAL)
- Externalities and their effects on long term energy policy for Europe as a whole and member states (27 region TIMES model, EC); potential contribution of renewable sources
- Common CO2 action and cross-border energy trade: modeling the energy system of Scandinavian countries (MARKAL)
- Market development potential of South East Europe (8 entities, MARKAL, USAID)
- Potential interconnections of some South East Asian countries (8 states, MARKAL, AUSAID)
- Supply options and interconnections of the Southern African Development Community region (14 states, TIMES)

C3—Example of national models for policy analyses

- Energy technologies assessment and CO2 mitigations (UK, MARKAL)
- Electric Supply Industry and CO2 mitigation (Germany, TIMES)
- Joint implementation of CO2 emission reduction measures between Switzerland and Colombia
- Endogenous learning of technology clusters progress (Europe single region, MARKAL-Matter)
- Evaluating mitigation policies for national communication to the UNFCCC (Italy, Belgium, etc.)
- Dematerialisation: integrated energy and materials systems engineering for GHG mitigation (MARKAL-MATTER-EU)
- CO2 emission reduction strategies and the role of nuclear energy (Japan, MARKAL)
- Evaluating the secondary environmental (SOx, NOx, VOC, PM) benefits of GHG mitigation policies (Belgium, MARKAL-Damage)
- Impact of opening the electricity market (Belgium, MARKAL)
C4 – Example of local models for policy analysis

- Solid waste management planning and local pollution studies (Genève, Switzerland)
- Air quality planning (Basilicata region, Italy)
- Energy environment planning models for transport systems in urban area (TIMES, Turin, Italy)
- Green lights and energy star building program for energy efficiency (Hong Kong, China)
- Optimal level of energy conservation, coupled production and district heating (Uppsala & other towns, Sweden)
- Long term strategic energy planning under varying boundary conditions (Mannheim, Germany)
- A Portfolio Approach in Local Energy Planning and Building Upgrades (New York, US)

C5 – Some ongoing projects using ETSAP tools

CHINA-4 Region MARKAL model, contributes to ETP 2008
CHINA-34P-TIMES model contributes to the Master Plan & Study
EC-CASCADE-MINTS: Case Study Comparisons and Development of Energy Models for Integrated Technology Systems
EC-NEEDS: The New Energy Externalities Development for Sustainability
EC-REACCESS: Energy corridors for a secure energy supply
EC-RES2020: Monitoring and Evaluation of the Renewable Energy Sources directives implementation in EU27
EC-TOCSIN: Technology-Oriented Cooperation & Strategies in India&China
EnerKey: Energy: Key Element of Sustainable Development of Joh’burg
MARKAL-MACRO-KAZAKHSTAN model, in the frame of the TACIS-project “Technical assistance to Central Asia Countries, climate change …”
US-NESCAUM NE12: The North-East States for Coordinated Air Use Management project
USAID-SEE-REDP: the Southeast Europe Regional Energy Demand Planning project
**D – Challenges ahead**

- Science: improve the theory underlying the technical-economic models
- Computation: elaborating more powerful algorithms for solving linear and non-linear technical-economic models
- Software: increase the speed and the ‘intelligence’ of managing huge problems (> 1 million equations)
- Statistics: extend energy balances to useful energy and energy services, integrate them with technology databases, environment inventories and macro-economic variables
- Make available to the users a technology database and better models

**E1 – Advantages of using ETSAP tools**

Energy (technology) systems are analysed for policy makers, in order to control how the system will develop and evaluate the impact of different control strategies (policies).

The energy system of each country is specific to the country, is different from all the others.

Would policy makers accept easily the conclusions of analyses prepared abroad?

ETSAP offers an internationally established (and reproducible) methodology for building a model tailored to the national circumstances, capable of identifying the control strategies most appropriate for the country – that can be different from other countries – and evaluating independently the effects and the impacts of national control strategies.
E1a – MARKAL–TIMES users across the world (>200)

E2 – Advantages of participating to ETSAP

- Free access to users' interfaces;
- Participation to the decision process;
- At the end of this year, full access to the ETSAP-TIAM (TIMES Integrated Assessment Model): a multi-region partial equilibrium model of the energy systems of 15 regions (Africa, Australia-New Zealand, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United States, and Western Europe) covering the entire World, with endogenous trade of energy and CO2 permits, stochastic variables and climate equations; it includes a procedure to subtract a country from its region and add it as a separate region.
F – The Energy Technology Systems Analysis Program

1. Program
2. Objectives
3. Strategy
4. Tasks
5. ETSAP tools users and participants
6. Participants

F1 – The Programme of Energy Technology Systems Analysis …

… is a multilateral international agreement, promoted and sponsored by the International Energy Agency (Paris).

This cooperation started after the first oil crisis, in order to understand through systems analysis, whether:

– alternatives to oil were technically feasible, economically and environmentally sustainable;
– solutions were global or dependent on national circumstances;
– global energy RD&D paths were possible or advantageous.

After two years of analyses (1976-77), since the tools available at the time were not sufficient to provide answers, the group developed a new tool, the MARKAL model generator.
**F2 – Objectives**

ETSAP experts assist decision-makers in assessing policies intended to meet the challenges of

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

... by carrying out

- a programme of co-operative energy technology systems analysis, and
- modelling studies of possible developments.

**F3 – Strategy**

The objectives are achieved through a twofold strategy:

1. ETSAP has established, and now maintains / enhances the flexibility of consistent multi-country energy / engineering / 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. In fact they implement several economic-equilibrium technology-explicit models of global, regional, national, and local systems.


**F4 – Tasks (Annexes)**

1976-77 Analysis of existing tools for evaluating R&D strategies
1978-80 MARKAL Model generator development (US-BNL, GE-KFA)
I. 1981-83 Energy Technology Systems Analysis Project
II. 1984-86 Information Exchange Project
III. 1987-89 International Forum on Energy Environment Studies
V. 1993-95 Energy Options For Sustainable Development
VI. 1996-98 Dealing With Uncertainty Together
VII. 1999-02 Contributing To The Kyoto Protocol
VIII. 2002-05 Exploring Energy Technology Perspectives
IX. 2003-05 Energy Models Users’ Group
X. 2005-07 Global Energy Systems and Common Analyses
XI. 2008-10 JJoint STudies for New And Mitigated Energy Systems (JOSTNAMES) (annual fee: 20k€ per participant)

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**F5 – Participants**

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

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

* open to new participants and sponsors