EFDA World TIMES Model

FINAL REPORT

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1. Introduction

The EFDA World TIMES project started on April 15, 2004 and was accomplished under the general direction of ORDECSYS, by KanORS, HALOA, and KUL.

These main objectives were:

- the construction of a Regionalized World energy/emission model based on the TIMES framework,
- its calibration to the initial year's (2000) IEA energy statistics and balances,
- the adaptation of the VEDA interface needed to manage the large databases and to operate the model,
- the testing of the model on demonstration scenarios, and
- the delivery of the model and the transfer of the required softwares and know-how to EFDA member teams.

The characteristics of the entire model are described in this report and its annexes, while the transfer of the required softwares and know-how was accomplished by means of presentations in Spring 2004, and a set of training sessions and model demonstrations at EFDA during the week of September 13-17. The model was installed and run on 11 computers attended by 14 participants from seven teams members of EFDA. The softwares' user's guides and database descriptions are provided as annexes to this report. The draft final report was delivered on September 14, 2004, one month before the end of the contract.

The main body of this report contains enough information to allow the reader a general understanding of the TIMES modeling system, its VEDA interfaces, the EFDA scenarios and databases, and typical results obtained from the model. This report is accompanied by several annexes containing detailed additional model and database descriptions, and user's guides for the VEDA Shell and report writer.

This rest of this report is divided into four main sections, treating successively: the general description of the TIMES model, the particularities of the EFDA model, some demonstration results, and a conclusion.

Acknowledgments

We gratefully acknowledge the efficient and diligent help provided by Giancarlo Tosato, our main contact at EFDA, all along the duration of the project. His advice and frequent feedbacks have considerably helped improve the conditions of our work, and, we hope, its quality. Any remaining imperfections of this report are of course our sole responsibility. We extend our thanks to the EFDA director and his

colleagues and staff for facilitating and animating our visits, and to the participants in the meetings, workshops, and training sessions, who demonstrated a real interest and involvement in the project, and thereby made our work easier and more effective.

2. The Tool

This section presents the various aspects of the TIMES model: after a brief model summary (section 2.1), we describe the main characteristics of TIMES (section 2.2), its mathematical formulation (section 2.3), its economic significance (section 2.4), and description of the front-end and back-end interfaces of the VEDA system (section 2.5).

2.1. The TIMES Model in a nutshell

TIMES (an acronym for The Integrated Markal Efom System) is an economic model of the energy system of one or several regions, that provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon.

Reference case estimates of end-use energy service demands (e.g., car road travel; residential lighting; steam heat requirements in the paper industry; etc.) are provided by the user for each region. In addition, the user provides estimates of the existing stock of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials.

Using these as inputs, the TIMES model aims to supply energy services at minimum global cost by simultaneously making equipment investment, operating decisions, primary energy supply decisions, and energy trade, by region. For example, in TIMES, if there is an increase in residential lighting energy service relative to the reference scenario (perhaps due to a decline in the cost of residential lighting, or due to a different assumption on GDP growth), either existing generation equipment must be used more intensively or new – possibly more efficient – equipment must be installed. The choice by TIMES of the generation equipment (type and fuel) is based on the analysis of the characteristics of alternative generation technologies, on the economics of the energy supply, and on environmental criteria. TIMES is thus a vertically integrated model of the entire extended energy system. The model fully qualifies as a tool for systems analysis.

The scope of the TIMES model extends beyond purely energy oriented issues, to the representation of some materials and environmental emissions related to the energy system. In addition, the model is admirably suited to the analysis of energy-environmental policies, which may be represented with accuracy thanks to the explicitness of its representation of technologies and fuels.

In TIMES – like in its MARKAL forebear –the quantities and prices of the various commodities are in equilibrium, i.e. their prices and quantities in each time period are such that at those prices the suppliers produce exactly the quantities demanded by the consumers. Further, this equilibrium has the property that the total surplus is maximized.

2.2. The Scenario Concept

The TIMES model is particularly suited to the *exploration* of possible futures based on contrasted *scenarios*. Given the long horizons simulated with TIMES, the scenario approach is really the only choice (whereas for the shorter term, econometric methods may provide useful projections). Scenarios, unlike forecasts, do not pre-suppose knowledge of the main drivers of the energy system. Instead, a scenario consists of a set of *coherent assumptions* about the future trajectories of these drivers, leading to a coherent organization of the system under study. A scenario builder must therefore carefully test the assumptions made for internal coherence, via a credible *storyline*.

In TIMES, a complete scenario consists of four types of inputs: energy service demands, primary resource potentials, a policy setting, and the descriptions of a set of technologies. We now present a few comments on each of these four components.

2.2.1. The Demand Scenario

In the case of the TIMES model, demand drivers (population, GDP, family units, etc.) are obtained externally, via other models or from accepted other sources. For instance, the EFDA TIMES model uses the GEM-E3 general equilibrium model to generate a set of *coherent* (total and sectoral) GDP growth rates in the various regions. Note that GEM-E3 itself uses other drivers as inputs, in order to derive GDP trajectories. These GEM-E3 drivers consist of measures of technological progress, population, degree of market competitiveness, and a few others, perhaps qualitative assumptions. For population and household projections, both GEM-E3 and TIMES use the same exogenous sources (United Nation and IPCC). Once the TIMES drivers are quantified, the construction of the scenario requires to compute a set of reference energy service demands over the horizon. This is done by choosing elasticities of demands to drivers, in each region.

As mentioned above, the demands are provided for the reference scenario. However, if the model is run is alternate cases (for instance for an emission constrained case, or for a set of alternate technological assumptions), it is likely that the demands will be affected. TIMES has the capability of estimating the response of the demands to the changing conditions of an alternate case. To do this, the model requires still another set of inputs, namely the assumed elasticities of the demands to their own prices. TIMES is then able to endogenously adjust the demands to the alternate cases without exogenous intervention. In brief, the TIMES model is driven not by demands but by demand curves.

To summarize, a demand scenario consists in a set of assumptions on the drivers (GDP, population, households) and on the elasticities of the demands to the drivers and to their own prices.

2.2.2. The Supply Scenario

The second constituent of a scenario is a set of *supply curves* for primary energy and material resources. In TIMES, each such supply curve, in each region, is multi-stepped, each step representing a certain potential of the resource available at a certain cost. In some cases, the potential may be expressed as a cumulative potential (e.g. reserves of gas, crude oil, etc), and in others, as an annual potential (e.g. for renewable resources such as wind, biomass, or hydro potentials).

2.2.3. The Policy scenario

Insofar as some policies impact on the energy system, they may become an integral part of the scenario definition. For instance, a No-Policy scenario may perfectly ignore emissions of various pollutants, while alternate policy scenarios may enforce emission restrictions, or emission taxes, etc. The detailed technological nature of TIMES allows the simulation of a wide variety of both micro measures (e.g. technology portfolios, or targeted subsidies to groups of technologies), and broader policies (such as general carbon tax, or permit trading system on air contaminants. A simpler example might be a nuclear policy that limits the future capacity nuclear plants. Another example might be the imposition of fuel taxes, or of industrial subsidies, etc.

2.2.4. The technological scenario

The fourth and last constituent of a scenario is the set of technical parameters assumed for the transformation of primary resources into energy services. In TIMES, these technical parameters are described in the form of technologies (or processes) that transform some commodities into others (fuels, materials, energy services, emissions). In TIMES, some technologies may be imposed, and others may simply be available for the model to choose. The quality of a TIMES model rests on a rich, well developed set of technologies, both current and future, for the model to choose from. The emphasis put on the technological database is one of the main distinguishing factors of models like TIMES. Other models will tend to emphasize other aspects of the system (e.g. interactions with the rest of the economy) and treat the technical system in a more succinct manner via aggregate production functions (see Annex 1, section 3)

Remark: Two scenarios may different in all or in only some of their components. For instance, the same demand scenario may very well lead to multiple scenarios by varying the primary resource potentials and/or technologies and/or policies, insofar as the alternative scenario assumptions do not alter the basic DM inputs (Drivers and Elasticities). The scenario builder must always be careful about the overall coherence of the various assumptions made on the four components of a scenario.

Technological Progress and Innovation: The large technological database offers many alternative technological choices to the model, as well as penetration potentials. It is the task of the TIMES model to endogenously select the degree of penetration of each technology. Therefore, TIMES endogenously determines the adoption rate of each technology and fuel present in the database, dynamically over the horizon.

2.3. The output of the TIMES model

A TIMES solution comprises the following information for each input scenario and each region or pair of regions:

- The investments in all technologies at each time period.
- The capacities and operating levels of all technologies at all time periods.
- The amounts of commodities (fuels, materials, emissions) produced, transformed, imported, exported, and consumed by each technology, at each time period.
- The demands for energy services at each period (which are different from the demands in the input scenario, if the run is not a reference run).
- The traded amounts of commodities between any two regions.
- The overall cost of the system, by period, or cumulative over the entire horizon[1].

[1] The absolute cost of a scenario has little meaning, because it ignores certain important fixed costs and revenues. Only the difference between the costs of two scenarios is meaningful.

- The price of each commodity at each time period, calculated as the marginal system value of that commodity.
-

2.4. Economic rationale of the TIMES model

This subsection provides a succinct economic interpretation of the TIMES partial equilibrium model. Partial equilibrium models have one common feature – they simultaneously configure the production and consumption of commodities (i.e. fuels, materials, and energy services) and their prices. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. A market is said to have reached an equilibrium at prices p^* and quantities q^* when no consumer wishes to purchase less than q^* and no producer wishes to produce more than q^* at price p^*. Both p^* and q^* are vectors whose dimension is equal to the number of different commodities being modeled. As will be explained below, when all markets are in equilibrium the total economic surplus is maximized.

The concept of total surplus maximization extends the direct cost minimization approach upon which earlier bottom-up energy system models were based. These simpler models had fixed energy service demands, and thus were content to minimize the cost of supplying these demands. In contrast, the TIMES demands for energy services are themselves elastic to their own prices, thus allowing the model to compute a *bona fide* supply-demand equilibrium. This equilibrium feature is present at every stage of the energy system: primary energy forms, secondary energy forms, and energy services.

TIMES is a partial equilibrium model based on maximizing total surplus defined as the sum of suppliers and consumers surpluses. This fundamental characteristic has several important consequences, which we briefly list below. These features are elaborated in more detail in Annex 1.

Outputs of a technology are linear functions of its inputs, which simply means that doubling the inputs of a technology doubles its outputs;
Total economic surplus is maximized over the entire horizon, and
Energy markets are competitive, with perfect foresight. As a result of these assumptions the following additional properties hold:

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

As a result of the linearity of the technologies, the equilibrium may be computed using the technique of Linear Programming (LP) for which powerful solvers are available.

Figure 1 sketches the partial equilibrium in the simple case where there is a single commodity.

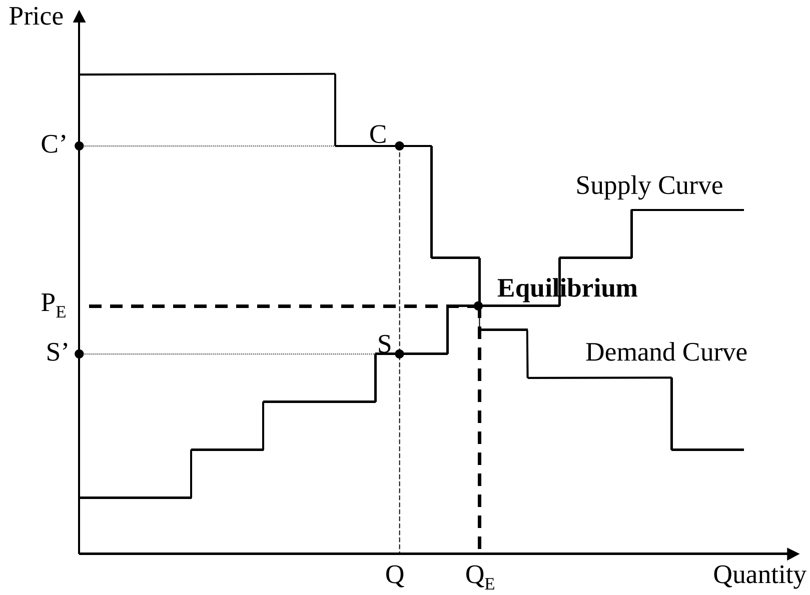


Figure 1. Supply-demand equilibrium with a single commodity

The Model interface: the VErsatile Data Analyst (VEDA)

A large and complex model such as TIMES requires a powerful set of tools for handling its large databases and results files. This is the task of the VEDA interface for TIMES, which is comprised of two independent components: VEDA-FE (front-end) for handling the input data and model runs, and the VEDA-BE (back-end) for aiding in the analysis of results and the preparation of result tables and graphics.

Each of these VEDA components has its user's guide (see Annex 5 for VEDA-FE and Annex 4 for VEDA-BE). In this section, we simply present the general structure of these two interfaces, and discuss their main characteristics.

2.4.1. A brief presentation of VEDA-FE

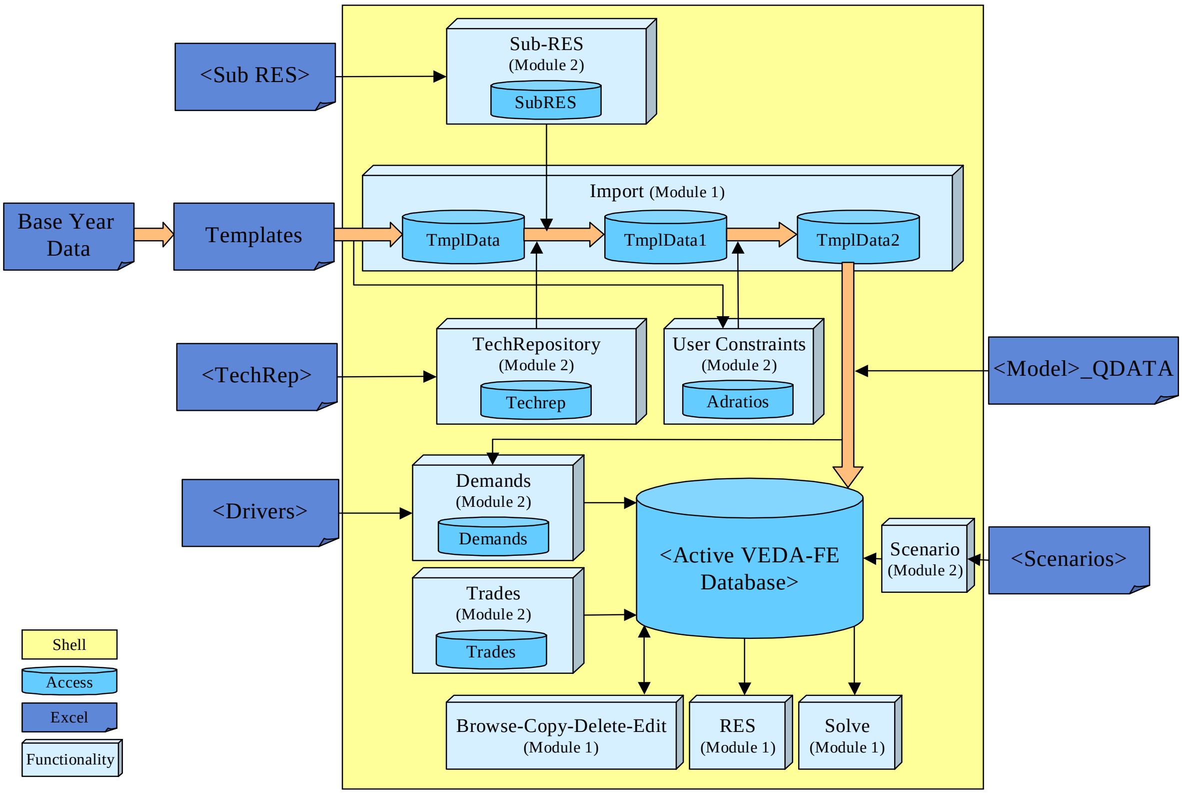


Figure 2. VEDA-FE Database Configuration

VEDA-FE is organized as a powerful combination of database files and spreadsheets, linked together by several modules. The shell takes advantage of the respective strengths of these two types of interfaces to provide maximum power and user friendliness. Figure 2 sketches the various VEDA-FE components, as well as the additional files used to provide portions of the input data. The components fall in three categories: Access Databases, Excel Spreadsheets, and VEDA modules, graphically represented by three different icons in Figure 2.

At any point of time, the entire model database is stored in the *Active VEDA database*. The database may be examined with the *VEDA Browser*, and it may be modified by a number of operations conducted via the various modules of VEDA-FE. We briefly present the modules as well as the external spreadsheets used by VEDA for importing input data.

VEDA-FE supports the user in four main aspects of model management, as follows:

- Constructing the initial model's database, using a variety of Excel source files as initial inputs, as well as internal VEDA functions;
- Browsing the components of the model via a variety of textual and graphic views;
- Modifying the model's input data; and
- Launching model runs.

The task of constructing an initial model database is accomplished using a set of *templates* whose function is to transform raw data from a variety of sources into an initial TIMES model. The first application of VEDA-FE was done for the SAGE model. A TIMES instance of VEDA-FE is very similar to a SAGE or a MARKAL version, the main differences arising from the different names of attributes in the various models.

We now turn to the description of four main aspect of the data management with VEDA: the content and location of the external input files and the databases, the data import process into VEDA-FE, the impacts of imports on edited data, and the concepts of database, scenario and run of the model.

2.4.1.1. Content and location of files

The VEDA-FE database is constructed from Excel files and Access databases (Figure 2). All VEDA-FE files are stored in two folders (and their sub-folders): the application folder, where VEDA-FE itself is installed, and the template folder, which may be anywhere on the computer. The Excel files used in the SAGE and the EFDA TIMES versions are:

a) The EFDA templates (<Region>_<Sector>_<Version>.xls; e.g. AFR_ELC_V7p0.xls). There are 75 such templates, one for each of the five sectors (see Table 1), for each region. The regional templates deal with broad sectors of the Reference Energy System (RES). The first two portions of the file name should not be changed, but the version may change. They contain:

- The model's basic structure (defining end-uses and sub-regions within a region).
- The fuel consumption by end-use in the base year.
- The energy production by fuel in the base year.
- The base-year end-use demands.
- The existing technology stock.
- The user constraints.
- The emission coefficients by fuel (VEDA-FE computes technology level coefficients based on the fuel inputs).
- Other model parameters (demand elasticities, discount rate, transmission efficiency, etc.).

In each sector, the energy production and consumption are calibrated in the templates to match the energy statistics and balances of the International Energy Agency (IEA) and data from the Office of Energy Markets and End Use (EMEU) for the initial time-period. In order to achieve calibration at future periods, certain user constraints are also constructed within each template. The ELC template describes central electricity and heat production including combined heat and power (CHP); the INDustry template deals with the industrial end-uses, and the industrial auto-electricity and CHP production; the RESidential and TRAnsportation templates describe the end-uses in these two sectors; the UPStream template describes fossil fuel extraction, renewable potential, and various fuel transformation processes including petroleum refineries. In effect, the templates also define the model's Reference Energy System
at the initial period (the RES may later be modified by adding appropriate fuels and technologies for subsequent periods). Template files are required for all regions being modeled.

b) The technology repository (<TechRep>.xls; e.g. TechRep_EFDA.xls). There is one file for the base scenario, which is located in the scenario folder. It contains the complete technical and economic data for all new technologies; they are listed on a separate sheet for each sector, the sector being specified by the sheet name. The user can create other files (with different names) to import new technologies into the repository and run different new technology scenarios. New commodities cannot be added through this facility; new commodities have to be defined in the templates first or via the sub-RES facility (see below). They need to be in the same format than the reference technology repository.

Table 1. List of regions and sectors for the EFDA model

Regions		**Sectors**	
AFR	Africa	ELC	Electricity production
AUS	Australia and New Zealand	IND	Industries
CAN	Canada	RES	Residential-Commercial-Agriculture
CHI	China	TRA	Transportation
CSA	Central and South America	UPS	Upstream
EEU	Eastern Europe		
FSU	Former Soviet Union		
IND	India		
JPN	Japan		
MEA	Middle East		
MEX	Mexico		
ODA	Other Developing Asia		
SKO	South Korea		
USA	United States		
WEU	Western Europe		

c) The driver's files (<Drivers>.xls; e.g. HighGDP.xls). There is one sample file in the scenario folder. A list of drivers, used to project demands, is already included in the Access database for demands. The user can create other files (with different names) to import new drivers in the database and run different demand projection scenarios (e.g. low economic growth and high economic growth cases).

d) The other scenario files (<Scenarios>.xls; e.g. Sce_ZDMFR.xls). There is one sample file in the scenario folder. The user can create a large variety of files (with different names) to import new scenario data in the database (e.g. bounds on emissions, technological discount rates, investment costs, etc.). Any parameter for an existing technology or commodity can be added through this facility.

e) The transformation file (EFDA_QDATA.xls). There is one transformation file, located in the application folder. This file is used to regionalize model parameters. The user can use arithmetic operations, to modify any technology parameter, or absolute values to replace existing ones or to insert new parameter values in the database. The user can only edit the original file, but cannot create other transformation files.

f) The sub-RES files (SUBRES_<Name>.xls; e.g. SUBRES_Hydrogen.xls). There are two files located in the application folder, in the 'SubRes_Tmpl' sub-folder. The first file (*SUBRES_Hydrogen.xls*) contains all the technologies related to the production and the consumption of hydrogen. The second file (*SUBRES_Hydrogen_Trans.xls*) is a transformation file (like *EFDA_QDATA.xls)* that applies only to the hydrogen sub-RES. This facility allows the user to isolate a part of the RES (e.g. the hydrogen production and consumption) and the possibility to include it or not in a model scenario.

At this point, it is useful to give indications to the user on the utilization of scenario files or the transformation file. Both files are used for modifying/augmenting the database. However, there are two basic differences: first, the scenario file is processed only at the time the scenario is imported, whereas the transformation file is processed each time (right after) the template import process is launched; and second, the scenario file may only be used to *add* parameters, while the transformation file may also be used to *modify* the existing values. A general guideline to choose between the two options when injecting parameter information, is that if an elaborate filter specification is being used to identify elements, and the user expects the resulting set to vary with changes in *TechRep_EFDA.xls*, then it is safer to use the transformation file approach; for example, to specify technology-specific discount rates for gas-fired power plants. If the set of elements is stable, then the scenario approach is preferable, as it saves processing time (example: declaring emission bounds).

2.4.1.2. VEDA-FE databases

The information and macros in the 6 types of external Excel files described above are used to create the final VEDA-FE database, using some intermediate Access databases. None of the Access databases require any direct intervention from the user. They are already present when VEDA-FE is first installed, and are modified exclusively from within the interface. However, it is useful to give some precisions to understand the whole configuration of the shell. The various Access databases are:

a) Intermediate databases: These databases are located in the templates folder. They contain the model data at three distinct steps of the main import process. The first (*TmplData.mdb*) contains only the template data, while the second contains new technology data in addition (*TmplData1.mdb*) and the third contains the user constraint data in addition of the first two (*TmplData2.mdb*).

b) Module 2 databases: These databases are located in the application folder. They contain the model data attached to four main modules of the interface: the demand projection module (*Demands.mdb*), the technology repository (*TechRep.mdb*), the user constraints (*Adratios.mdb*) and the energy/emission permit trades (*Trades.mdb*). These four modules constitute the main functions of VEDA-FE and are described below.

2.4.1.3. The VEDA-FE Modules

Multiple functionalities offer the user powerful and intuitive ways to view and edit information. These are grouped into two main menus. The functions in module 1 impact the entire model database, while the functions in module 2 menu impact the following databases: Demands, Technology Repository, Trades, User constraints, and Scenario Data. These functionalities are briefly introduced here in order to get a comprehensive view of the system.

Module 1 menu:
Import: To import the information from the templates, as well as the information from the new technology and the user constraint modules. It compiles all these data, along with a transformation process (via the *EFDA_QDATA.xls* file, into a VEDA-EFDA database. Orange block arrows represent this import process.

Browse-Copy-Delete-Edit: To browse the complete database and to copy, delete or edit data. Any changes are then recorded in the active database.
RES: This function allows seeing a graphical representation of the regional RES and of the endogenous trade links.
Solve: To set various model and solver options, and to submit runs.

Module 2 menu:
Demands: To view and edit demand projections and to manage driver data and calibration/sensitivity series. Any changes are recorded in the *Demands.mdb* database and in the active database.
Technology Repository: To view, select and modify the new technologies to be used in each region, and to import new technologies in the repository. Any changes are then recorded in the *TechRep.mdb database*.
Trades: To declare trade links and parameters between regions for energy commodities and emission permits. These specifications are recorded in the *Trades.mdb* database and in the active database.
User constraints: To view and edit user constraint/market share definitions and coefficients, to delete or copy user constraints and to add new user constraints. Changes are recorded in the *Adratios.mdb* database.
Scenario Data: To import new scenario data in the database. New data are then recorded in the active database.

2.4.1.4. The import process

Orange block arrows represent the main import process of files to create the active VEDA-FE database. This import process is launched via the Import menu (module 1) and each step is associated with a different color in the template manager (see Figure 3):
Step 1 (Yellow: IEA Update). To update the energy numbers in the templates from the Base-Year files (IEA/EMEU databases). This step is not required for the EFDA case.
Step 2 (Red: Template Import). To read the information in the templates. This step is required for each template that has been modified. Databases affected: TmplData.MDB.
Step 3 (Orange: Technology Repository). To import the new technologies. Databases affected: TmplData1.MDB, TechRep.MDB.
Step 4 (Light green: Transformation). To compile all above information, along with the transformation file (*EFDA_QDATA.xls*), into the VEDA-FE database.
Step 5 (Pink: User Constraints). To generate the user constraints. Databases affected: TmplData2.MDB, Adratios.MDB.
Step 6 (Dark green: Update Database). To update the active VEDA-FE database with the information compiled in the TmplData2.mdb database.
Blue color indicates that the import process is complete.

Therefore, as a first step, the user imports the information from the templates (*<Region>_<Sector>_<Version>.xls; e.g. AFR_ELC_V7p0.xls*) and from the new technology (*TechRep.mdb*) and the user constraint (*Adratios.mdb*) databases. All these data are compiled, along with a transformation process (*EFDA_QDATA.xls*) into a VEDA-FE database. With the information included in the other two modules *(Demands.mdb* and *Trades.mdb*), these data constitute the active VEDA-FE database. Afterward, the user can also import new data, compiled in Excel files, from various menus (module 2) of VEDA-FE: new technologies (*e.g. TechRep2_EFDA.xls*) via the Technology Repository menu, new demand drivers (*e.g. HighGDP.xls*) via the Demands menu and any new scenario data (*e.g. Sce_ZDMFR.xls*) via the Scenario Data menu.

The user can use the multiple VEDA-FE functionalities to view or edit the entire EFDA database. The impacts of importing on edited data are described in the next section. More especially, it consists in clarifying, which changes are permanent and which ones are temporary (until the next import process).

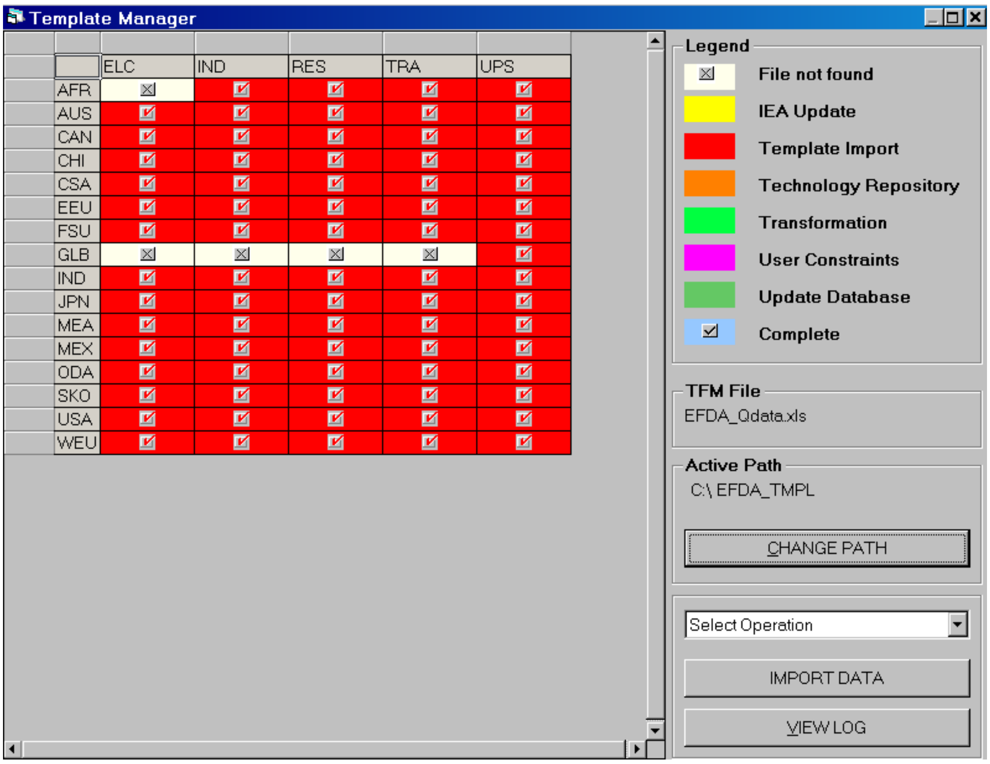


Figure 3. Template Manager of VEDA-FE

2.4.1.5. Impacts of imports on edited data

It is exceedingly important for the user to know which actions performed through VEDA-FE functionalities have a permanent impact, and which actions have a temporary impact only, “permanent” being defined as something that survives the import process. The user can edit data through the browser of the module 1 menu (for the whole database), and from the functionalities of the module 2 menu (for specific databases): Demands, Technology Repository, Trades, User constraints, and Scenario Data. The impacts of importing on edited data are explained according to the different steps of the import process described above.

Browser: The user can edit any data of the model from the browser. All base scenario modifications are temporary; they are lost with future imports of templates (from step 2). However, since the import process is performed on a region basis, the import of templates for a particular region will not affect the modifications done in the database for other regions.
The only way to retain modifications for the base scenario is to use the copy function to create a new scenario.
As for other scenarios than base, modifications are lost only if that particular scenario is re-imported (via the Scenario Data function of module 2 menu).

Technology Repository: From this functionality, the user can modify the selection of the new technologies available for each region. These modifications are saved only in the module database (TechRep.mdb). Consequently, a re-import is required from step 3, for regions and sectors involved, to update the VEDA-FE database. Future imports of templates (from step 2) do not affect these modifications.
The user cannot edit the new technology parameters at this level. These modifications are done directly in the technology repository Excel file (*e.g. TechRep_EFDA.xls*). Then, this file is re-imported via the technology repository (module 2 menu) and the main import process is needed from step 3 for all regions. Since the new technology repository is built on a sector basis, a modification in one or more sectors has an impact on all regions at the same time.
The selection of the new technologies available in each region remains valid when the same new technologies (with the same name, but with the same or different parameter values) are re-imported from this module. If other new technologies are imported (*e.g. TechRep2_EFDA.xls*), it is the user’s responsibility to make the selection of new technologies available in each region.
At this point, one needs to perform the import step after importing new technology definitions, and/or changing technology selections. This is to assign the fuel combustion based emission coefficients, and to regenerate the user constraints.

User constraints: From this functionality, the user can modify the definition or the coefficients of existing user constraints, and create

new user constraints. These modifications are saved only in the module database. Consequently, one needs to perform the import operation from step 5, for regions and sectors involved, to update the database. A clear distinction is maintained between the constraints read from the templates, versus those created within the application. While either can be modified within the application, the ones that come from the templates are restored to the template definitions when the import operation is performed. However, the import process does not affect the ones defined within the application. Finally, relaxation factor provides an easy way to relax user constraints. To summarize:
A re-import process from step 3 (technology repository) will not affect the user constraint definition and coefficient modifications.
The relaxation factors applied to existing user constraints within VEDA-FE are retained, since they are not read from the templates.
The new user constraints and market shares created within VEDA-FE are retained.

Demands: From this functionality, the user can modify demand projections through a selection of drivers and calibration/sensitivity series. These modifications are updated in the database as the user saves and exits the module and any other import is needed. Future imports of templates (from step 2) do not affect these modifications for future periods (2005 to 2050). However, imports of templates affect the base year value (i.e. at the time-period 2000), because it is where they are calculated. If the base year values have changed in the templates, the new demand projections are calculated during the import process. This calculation is based on the driver and the calibration/sensitivity series that are selected for each demand. Changes are updated in the active database as the user exits this module. Therefore, no need to perform the import step after making modifications in the demand module.

Trades: From this functionality, the user can create, and then modify, trade links and parameters. These declarations and modifications are updated in the database as the user saves and exits the module and any other import is needed. Future imports of templates (from step 2) do not affect any of the declarations and modifications.
There is only one exception: if some of the technologies created for the endogenous trades qualify for some user constraints. At this point, nothing informs the user, if trade declarations or modifications require a re-import of user constraints. It is the user's responsibility to re-import the user constraints (from step 4) for the appropriate regions and sectors.
Changes are updated in the active database as the user exits this module. Therefore, no need to perform the import step after making modifications in the demand module.

In summary, a re-import of templates (from step 1 or step 2) overwrites edited base year demand values (2000 period), user constraint definition and coefficients, existing technology parameters and other parameters existing in the templates (demand elasticities, discount rate, etc.) for regions that need to be imported. On the other hand, re-importing templates does not affect demand projections (from 2005 to 2050), new technology selection (by regions) and parameters values, any trade links or parameter values and any other scenario data than base.

2.4.1.6. Concepts of database, scenario and run

It is important to define the concepts of active database, scenario and run as they are mentioned in this guide.

Active database. The previous sections have described in detail the concept of an active VEDA-FE database and explained the impacts of imports on edited data within a single active database. However, the user can create several versions of the active database (but can open only one at the same time). It is useful to explain the impacts of creating a new active database on edited data.

To create a new active database, it is necessary to re-import data. If the previous active database was complete (*Color Blue: Complete*), an import is needed from the transformation stage (*Step 6; Dark green: Update Database*). Given that all data are compiled in Access databases, the import process is not required from the first steps when these databases have not changed. If the previous active database was not complete for some regions and sectors (*Step 1,2,3,4 or 5*), an import is needed from the same stage. In this case, an import is also needed from the transformation stage (*Step 5; Light green: Transformation*) for all other sectors of those regions for which the database was not completed. Indeed, imports of templates will have impacts on edited data as explained in the previous section. Within a new active database, it is also necessary to re-import the scenario's files, the driver's files and other technology repositories for other scenarios than base.

To create different active databases, the same Access files are always updated with imports. In other words, only one copy of each of the Access database is used at the same time to create the active database. Consequently, it is not possible to keep several active databases in VEDA-FE with different changes in the various modules. Nevertheless, it should be mentioned that there exists an indirect way to store alternate databases, by making copies of the four Access databases (*Demands.mdb*, *TechRep.mdb*, *Adratios.mdb, Trades.mdb*), into specific directories. Later, these copies may be brought back to the VEDA directory to become the active database.

Scenario. The base scenario, as defined in this guide, includes data from the templates (*<Region>_<Sector>.xls*), from the transformation file (*EFDA_QDATA.xls*) and from the four module databases (*Demands.mdb*, *TechRep.mdb*, *Adratios.mdb, Trades.mdb*). The concept of other scenarios applies to any other data imported into the active database from external Excel files: new technologies (*e.g. TechRep2_EFDA.xls*) via the Technology Repository menu, new demand drivers (*e.g. HighGDP.xls*) via the Demands menu and any new scenario data (*e.g. Sce_ZDMFR.xls*) via the Scenario Data menu. Each of these extra files constitutes a different scenario.

Run of the model: The model is always solved using the base scenario information, and one or more other scenario(s). The other scenarios can be included or excluded at the time of solving. Therefore, different runs (with different names) can be sent using the base scenario information plus different other scenario data. The run name appears as the name of the results files for VEDA-BE.

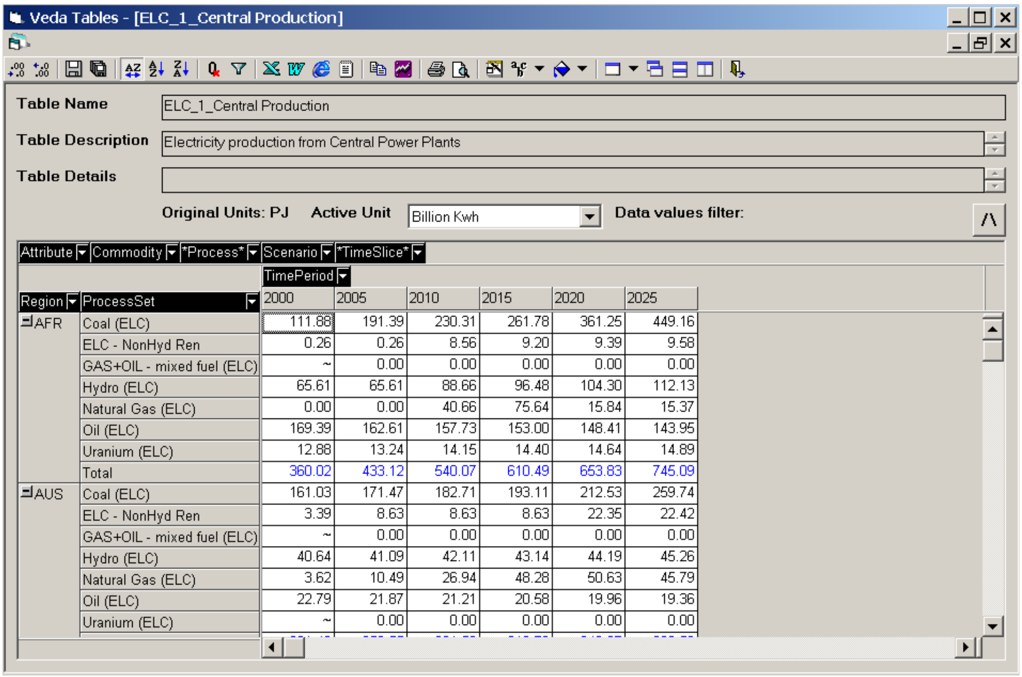
2.4.2. A brief presentation of VEDA-BE

The **VE**rsatile **D**ata **A**nalyst Back-End module (VEDA-BE) is a software dedicated to the analysis of data and results and to the production of result tables and graphs to help in the examination of results from a variety of complex mathematical models. The latest version of the tool adapts easily to almost any model characterized by multiple indexation of the variables of interest, including MARKAL, TIMES, and many other energy or economic models. The software may function in interactive or batch mode, for debugging a trial run or for producing a series of standard or custom result tables for a report.

2.4.2.1. The Table Concept

In VEDA-BE, the user creates *analysis tables* by flexibly choosing their contents and their layout. Figure 4 shows a typical example of a VEDA Table.

The Table is the main object of VEDA-FE. A table is determined by three types of choices: the selection of what *type of result* to include in it, the selection of what *dimensions* to show (or hide), and the selection of the *layout* to be used. We briefly explain these three choices and briefly mention the VEDA features designed to handle them, using TIMES hypothetical examples.



Region	ProcessSet	2000	2005	2010	2015	2020	2025
AFR	Coal (ELC)	111.88	191.39	230.31	261.78	361.25	449.16
	ELC - NonHyd Ren	0.26	0.26	8.56	9.20	9.39	9.58
	GAS+OIL - mixed fuel (ELC)	~	0.00	0.00	0.00	0.00	0.00
	Hydro (ELC)	65.61	65.61	88.66	96.48	104.30	112.13
	Natural Gas (ELC)	0.00	0.00	40.66	75.64	15.84	15.37
	Oil (ELC)	169.39	162.61	157.73	153.00	148.41	143.95
	Uranium (ELC)	12.88	13.24	14.15	14.40	14.64	14.89
	Total	360.02	433.12	540.07	610.49	653.83	745.09
AUS	Coal (ELC)	161.03	171.47	182.71	193.11	212.53	259.74
	ELC - NonHyd Ren	3.39	8.63	8.63	8.63	22.35	22.42
	GAS+OIL - mixed fuel (ELC)	~	0.00	0.00	0.00	0.00	0.00
	Hydro (ELC)	40.64	41.09	42.11	43.14	44.19	45.26
	Natural Gas (ELC)	3.62	10.49	26.94	48.28	50.63	45.79
	Oil (ELC)	22.79	21.87	21.21	20.58	19.96	19.36
	Uranium (ELC)	~	0.00	0.00	0.00	0.00	0.00

Figure 4. Typical example of a VEDA Table

2.4.2.2. Constructing VEDA Tables

Choosing the type of result to show amounts to specify one or more attributes or combination of attributes (for instance the energy output as shown in Figure 4). VEDA makes this task quite easy by offering a list of ready-made attributes (Table 2), and by allowing the combination of attributes in user-defined arithmetic expressions via its *aggregation* function.

The *dimension* roughly corresponds to an index of the model's variables, such as: region, time period, process, commodity, time-slice, scenario, and vintage (to this list, TIMES adds *Data Value* dimension, which may be *Primal* or *Dual*). The TIMES dimensions are shown in the left portion of the main VEDA screen shown in Figure 5.

By default, a table would include all elements in a dimension (for instance all regions, all time periods, etc.). In many cases however, it is desirable to restrict the elements to be shown in each dimension (for instance, show only some processes, a few time periods, etc.). In the example in Figure 4, only two regions have been selected, and only electricity generation processes have been selected. In VEDA, the choice of which elements to include in (and/or exclude from) a dimension is accomplished via *filtering*, using the powerful and user-friendly *search engine* embedded in the software. The search engine allows the user to filter elements in or out of a dimension, using the name of the element, and/or the kind of inputs or outputs it is associated with.

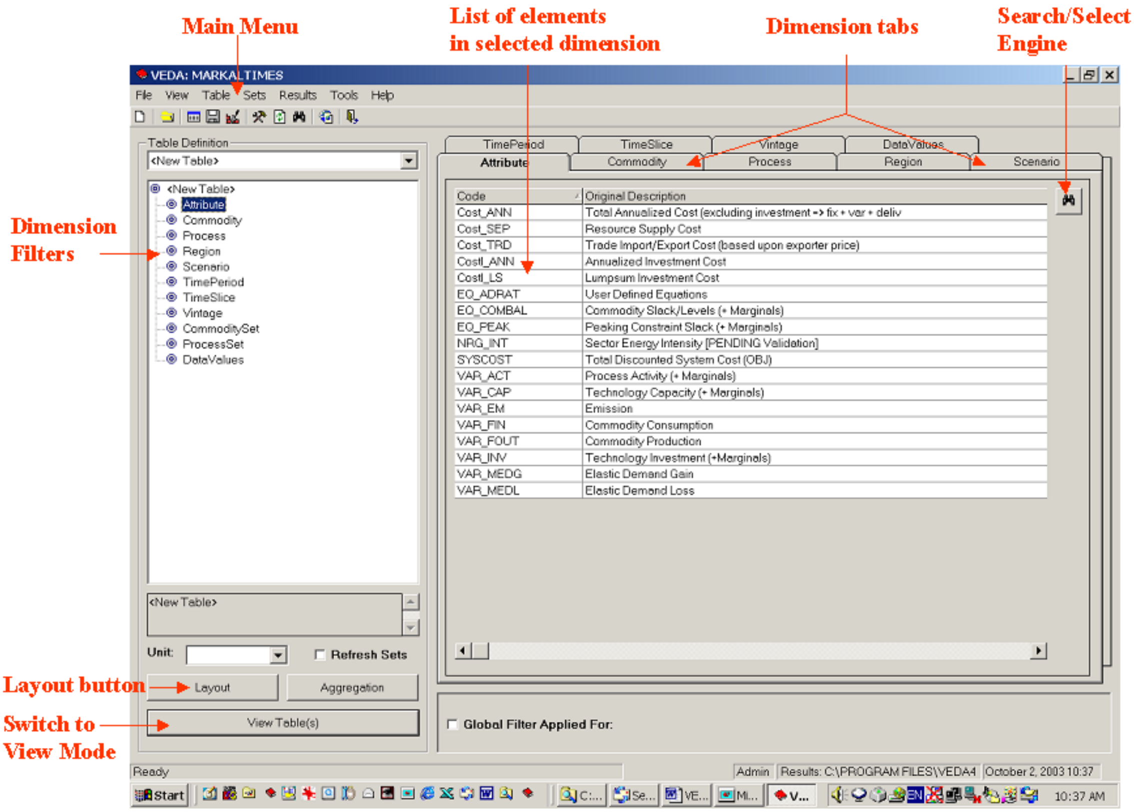


Figure 5. Main screen of VEDA-BE

Another extremely powerful tool is available in VEDA to help filter the elements along any dimension, namely, the creation of *sets*. Each set regroups elements of a like nature along some dimension, for use in tables. Sets may be considered as the result of pre-filtering elements, and they are stored in VEDA for later use in any other table. For instance, the table shown in Figure 4 uses seven sets of processes (Coal Elc, ELC-nonhyd Ren, etc.), each regrouping electricity generation technologies of a certain kind. Sets are therefore worth defining it is anticipated that they will be used more than once. They are most useful for the process and commodity dimensions, since these dimensions have many elements. Some sets are pre-defined in VEDA, but the user may create any sets he likes using the search engine. The search engine allows the user to filter elements in or out of a set, using the name of the element, and/or the kind of inputs or outputs it is associated with. Sets may also be constructed by including and/or excluding other sets.

The *layout* of each table is chosen by the user via simple drag-an-drop operations, and may be stored for later use on other tables. In particular, the user may put a particular dimension *on* the table or take it *off* the table. When a dimension in on the table, its elements are explicitly listed as columns or rows, and it is easy to change their position from row to column and vice versa. When a dimension is off the table, its elements are still (implicitly) present, and the attributes are summed over all the elements.

Other layout and formatting features include: showing/hiding the zeroes or small values, or large values in a table; creating additional rows/columns to show totals and subtotals; choosing the number of decimals; sorting the table values in ascending or descending order; etc.

Table 2. List of VEDA-BE attributes

VEDA attribute	**Dimensions involved**	**Description**
COST_act	P	Annual variable activity costs of processes (undiscounted)
COST_com	C	Annual commodity costs (including costs of import/export) Undiscounted
COST_dec	C	Annualized capital cost of decommissioning; costs for capacity related commodities released during decommissioning (generated by COST_FLO). Undiscounted.
COST_els	C	Annual elastic demand cost term. Undiscounted
COST_flo	p,c	Annual flow costs. Undiscounted.
COST_fom	P	Annual fixed operating and maintenance costs. Undiscounted.
COST_inv	P	Annualized investment costs. Undiscounted.
COST_late	r,y,p, with y after EOH	Annual late costs: Salvage value for capacity related commodity costs of commodities that are released during decommissioning of a plant. Undiscounted.
COST_salv	r,v,p (with v being the investment period)	Salvage costs by process and investment period; NOT annualized. Undiscounted.
EQ_combal	C	Commodity Slack/Levels: commodity production minus consumption (production does not include constants such as recycled commodity at dismantling time of past investment).
EQ_combalM	C	Commodity shadow price
EQ_peak	C	Peaking Constraint Slack
EQ_peakM	C	Peaking Constraint shadow price (price premium for consumption during peak time slice paid by the consumer in addition to COMBAL price)
ObjZ	None	Total discounted present value of system cost
PAR_capLO	P	Capacity Lower Limit
PAR_capUP	P	Capacity Upper Limit
PAR_PastI	P	Capacity Past Investments
User_ConFXM	uc_n,t,r,t,s (with uc_n being name of user constraint)	User constraint shadow price, for equality constraints.
User_ConLOM	uc_n,t,r,t,s	User constraint shadow price for greater than or equal constraints
User_ConUPM	uc_n,t,r,t,s	User constraint shadow price, for less than or equal constraints
VAR_act	P	Process Activity level
VAR_actM	P	Process Activity reduced cost
VAR_cap	P	Technology Capacity

VEDA attribute	**Dimensions involved**	**Description**
VAR_capM	P	Technology Capacity reduced cost
VAR_comnet	C	Commodity Net quantity (consumption minus production). Only generated when bound is specified by the user (COM_BNDNET)
VAR_comnetM	C	Dual variable of bound put on the net production (VAR_COMNET) of a commodity
VAR_comprd	C	Commodity Total Production; only generated when bound is specified by the user (COM_BNDPRD)
VAR_comprdM	C	Dual variable of constraint related to the bound of VAR_BNDPRD
VAR_fin	p,c	Commodity Consumption by Process
VAR_fout	p,c	Commodity Production by Process
VAR_ncap	P	Technology Investment
VAR_ncapM	P	Technology Investment reduced cost

* In addition, the r, t, s, v, dimensions are involved for attributes involving processes, and the r,t,s dimensions for attributes involving commodities only.

2.4.2.3. Other VEDA functionalities

VEDA tables may be *exported* to an Excel spreadsheet, a Word file, or a Text file. It may also be *printed*. Graphs in two and three dimensions may be created at the click of a button.

The *RES VEDA feature* is of a different nature. It allows the analyst to examine the results in the context of the RES itself. Key results concerning processes and commodities are shown on a graphic image of the portion of the RES concerned with these results. This feature is especially useful when debugging a run.

3. The EFDA World TIMES Model

Whereas the previous sections have dealt with the features and tools common to all TIMES models, this section describes the specific instance developed for the EFDA project. The reader should therefore keep in mind that some or all of the information of this section is subject to future changes by the model users, and is of interest only for demonstration purposes. We start with a succinct description of the EFDA RES, and then proceed to describe the demand scenarios prepared for this project. The complete technological database will not be presented in this report due to its excessively large size, but is accessible in its entirety via the VEDA-FE interface.

3.1. The EFDA Reference Energy System

This section briefly describes the Reference Energy System (RES) of the EFDA World-TIMES model. The details of the RES structure (list of demands, types of technologies and fuels, naming conventions, etc.) are presented in Annex 2. The complete database (including the values of the technological and economic parameters) is best accessed via the VEDA-FE browser, as it contains an exceedingly large amount of quantitative information. However, this section gives a concise idea of the entire EFDA model data.

Table 3. List of regions in World-TIMES

Code	**Region**
AFR	Africa
AUS	Australia-New Zealand
CAN	Canada
CHI	China
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East
ODA	Other Developing Asia
SKO	South Korea
USA	United States
WEU	Western Europe

Regions. The model is disaggregated into 15 regions (Table 3). Each regional model is a complete, self-contained TIMES model. In addition, the 15 models are hard-linked by several energy and emission permit trading variables. The database also distinguishes between the trading of oil and petroleum products produced by OPEC and non-OPEC regions.

Time horizon. The model is run over a 107-year horizon (1998-2104), divided into 12 periods, centered in 2000, 2005, 2010, 2020, ..., 2100 (Table 4). This definition leads to time periods of variable length.

Table 4. Definition of the time periods

Period Number	Starting year	Ending year	Center	Number of Years
1	1998	2002	2000	5
2	2003	2007	2005	5
3	2008	2012	2010	5
4	2013	2027	2020	15
5	2028	2032	2030	5
6	2033	2047	2040	15
7	2048	2053	2050	6
8	2054	2066	2060	13
9	2067	2074	2070	8
10	2075	2085	2080	11
11	2086	2095	2090	10
12	2096	2104	2100	9

Figure 6 illustrates the reference energy system of a region in the World-TIMES model. The numbers of technologies are shown in brackets within each sectoral box. There are more than 1400 technologies in each region. The fuels are indicated along the links of the RES. Each generic fuel name stands for a number of fuels. For instance, the generic name COM*** stands for the set of fuels used in the commercial sector (COMELC, COMOIL, COMNGA, etc.). The total number of distinct fuels exceeds 100.

Demands. In each region, 42 demand segments cover five end-use sectors: residential (11 segments), commercial (8 segments), agriculture (1 segment), industry (8 segments) and transportation (15 segments). Each demand segment is serviced by end-use technologies, whose number varies depending on the segment, as indicated by the figures within brackets in each box of Figure 6. These figures indicate the number of existing and future technologies available in each sub-sector. They are projected up to 2100 using socio-economic drivers, such as population and GDP, and elasticities of the service demands to these drivers, as discussed in section 3.3.

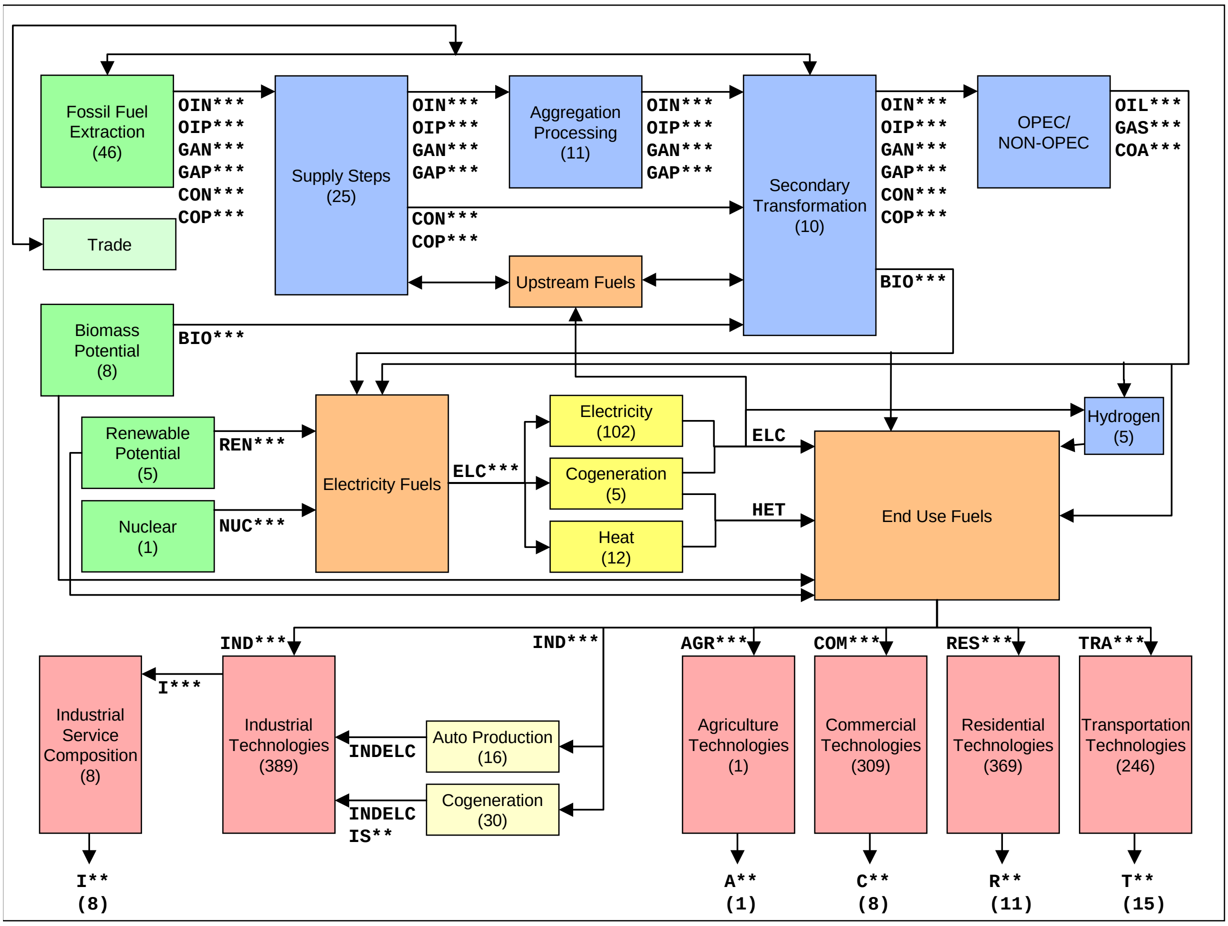


Figure 6. The reference energy system of a region in World-TIMES

Supply. The energy production sector is represented by three distinct blocks: primary production, secondary transformation, and production of electricity and heat. Primary production delivers the raw fossil fuels, biomass, and nuclear fuel from existing and future potentials. Crude Oil, gas and coal resource availabilities are provided for each region. They cover located reserves, reserve growth and new discovery for conventional oil, mined oil sands, ultra heavy oil, shale oil, natural gas, hard coal, and brown coal. Unconventional and unconnected gas resources are also available. The cost curves of reserves and extraction technologies have each 3 steps of increasing unit cost, reflecting the increase of extraction cost with the cumulative level of extraction. Primary biomass includes solid biomass, landfill gas, liquids from biomass, energy crops, industrial and municipal wastes. This block also contains the potentials for other renewable energy forms (geothermal, hydroelectricity, wind, etc.). Secondary transformation transforms the primary energy forms into fuels for the end-use sectors and for electricity and heat generation. The secondary transformation of oil products is represented mainly via a flexible refinery technology.

The production of electricity and heat is technologically explicit and detailed. Available power plants include technologies such as conventional pulverized coal, integrated coal-gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), diesel plants, fuel cells, biomass plants, nuclear, hydro-electricity, wind, solar, etc. Co-firing power plants are available for both coal and gas fired plants. Electricity production (and consumption) is tracked in three seasons and two divisions of the day, resulting in six time slices annually. In addition, there is a power constraint representing the peak reserve electricity requirement in each period. Heat is tracked by season only (3 time slices). Fuels produced and consumed in each sector generally represent a mix of different energy commodities (e.g. a mix of distillates, gasoline and other oil products for the residential sector).

Hydrogen may be generated by electrolysis of water, reforming of natural gas and partial oxidation of coal, with and without CO2 capture. It can be consumed either as a pure commodity in the transportation sector or mixed with natural gas in industry and residential/commercial sectors.

Emissions. The model tracks emissions of CO2, CH4, and N2O from the energy system. Combustion emissions are based on the fuel inputs of technologies. For fugitive emissions (due to losses and venting) and emissions related to non-energy consumption (like feedstock), emission coefficients are specified at the technology level.

International trade. The trade of natural gas, liquefied gas, and coal is endogenously modeled. Thus, the amount and price of each of these traded commodities is endogenously computed as part of the equilibrium solution. Electricity is not traded at the interregional level, except between USA and CAN, where exchanges have been fixed, by default, at their 2000 values. In contrast, the prices of traded crude oil and refined petroleum products are exogenously specified to reflect the non-competitive world market for oil. Each region is free to import any amount of crude oil and/or refined petroleum products at an exogenous price in each period. Exports are then adjusted ex-post to balance imports at the world level. International trade of hydrogen is not modeled.

Zero-emission-technologies and carbon sinks. Because of its impact on the cost of abating CO2 emissions, sequestration of CO2 is modeled. It includes: capture, which may occur at power plants (IGCC, pulverized coal, NGCC, solid oxide fuel cell SOFC) and at hydrogen plants; storage (oil/gas fields, coal bed methane recovery, aquifers, deep ocean, mineralization) and transportation between capture and storage. Sequestration by forests is also available. Capture at industry level is not included in the current database.

Economic parameters. GDP and all costs and prices are expressed in constant (year 2000) US dollars, calculated at market exchange rates (MER) for all regions. Investment, variable and fixed costs of technologies vary across regions in order to reflect differences of labor costs and productivity, land costs, and project boundaries. The overall annual discount rate used for calculating the net present value of the system is fixed at 5%. Some sector and region specific discount rates (hurdle rates) are also used for annualizing investment costs, in order to reflect the financial and behavioral characteristics appropriate to each economic agent.

3.2. Calibration to Initial Year

The VEDA-FE model shell includes an aid to automatize the calibration of the entire model to some specified year and data sources. The initial year is 2000, and the basic data source is the 1999 Energy Statistics and Balances of OECD and Non-OECD countries from the International Energy Agency.

3.3. The construction of the EFDA Demand Scenarios

A demand scenario is constituted by a set of annual demands for energy services, for each region and each future period of the planning horizon. The demand projections do not purport to be forecasts. Instead, following the approach of the IPCC SRES group (ref), we construct a set of reference demands that are a coherent set of projections forming a particular view of the future. We now describe the approach taken to construct the reference demand scenario. It consists of four steps:

<u>Step 1</u>: define a set of socio-economic drivers such as GDP, Population, Number of Households, etc., and assign a driver to each particular demand category (assigned drivers may be region and time dependent);
<u>Step 2</u>: obtain projections for each driver for each region, each time period;
<u>Step 3</u>: Choose elasticities of each demand to its assigned driver (may be region and time dependent);
<u>Step 4</u>: Compute each demand.

The next four subsections explain and illustrate these four steps.

3.3.1. The Drivers

The list of selected drivers appears in Table 5, whereas the assignment of drivers to demands is shown in Table 6. The next section discusses the other steps of the process.
Remark: Each step of constructing the demand projections is accomplished within VEDA-FE.

Table 5. List of drivers

Code	Description
GDP	GDP growth rate
POP	Population growth rate
HOU	Household growth rate
SPROD_A	Agricultural production growth rate
GDPP	GDP per capita growth rate
	Sectoral production growth rates in 3 broad industrial sectors:
SPROD_I	- Energy intensive industries
SPROD_O	- Other industries
SPROD_S	- Services

Table 6. Assignment of drivers to demands (all regions)

Demand code	Demand description	Driver before 2050	Driver after 2050
AGR	Agriculture	SPROD_A	SPROD_A
Commercial Sector			
CC1, CC2, CC3, CC4	Space cooling	SPROD_S	SPROD_S
CCK	Cooking	SPROD_S	SPROD_S
CH1, CH2, CH3, CH4	Space heating	SPROD_S	SPROD_S
CHW	Hot water heating	SPROD_S	SPROD_S
CLA	Lighting	SPROD_S	SPROD_S
COE	Electric equipments	SPROD_S	SPROD_S
COT	Other energy uses	SPROD_S	SPROD_S
CRF	Refrigerators and freezers	SPROD_S	SPROD_S
Industrial Sector			
I00	Very other industries	GDP	GDP
ICH	Chemicals	SPROD_I	SPROD_I
IIS	Iron and steel	SPROD_I	SPROD_I
ILP	Pulp and paper	SPROD_O	SPROD_O
INF	Non ferrous metals	SPROD_I	SPROD_I
INM	Non metal minerals	SPROD_I	SPROD_I
IOI	Other industries	SPROD_O	SPROD_O
NEO	Industrial and Other Non Energy Uses	GDP	GDP
ONO	Other non specified energy cons.	GDP	GDP
Residential Sector			
RC1, RC2, RC3, RC4	Space cooling	GDPP	HOU
RCD	Cloth dryers	GDPP	HOU
RCW	Cloth washers	GDPP	HOU
RDW	Dish washers	GDPP	HOU
REA	Miscellaneous electric energy	GDPP	GDPP
RH1, RH2, RH3, RH4	Space heating	HOU	HOU
RK1, RK2, RK3, RK4	Cooking	POP	POP

Demand code	Demand description	Driver before 2050	Driver after 2050
RL1, RL2, RL3, RL4	Lighting	GDPP	GDPP
ROT	Other energy uses	GDPP	HOU
RRF	Refrigerators and freezers	GDPP	HOU
RWH	Hot water heating	POP	POP
Transportation Sector			
TAD	Domestic aviation	GDP	GDP
TAI	International aviation	GDP	GDP
TRB	Buses	POP	POP
TRC	Commercial trucks	GDP	GDP
TRE	Three wheelers	POP	POP
TRH	Heavy trucks	GDP	GDP
TRL	Light trucks	GDP	GDP
TRM	Medium trucks	GDP	GDP
TRT	Autos	GDPP	GDPP
TRW	Two wheelers	POP	POP
TTF	Freight rail transportation	GDP	GDP
TTP	Passengers rail transportation	POP	POP
TWD	Internal navigation	GDP	GDP
TWI	International navigation (bunkers)	GDP	GDP
NEU	Non-energy uses in transport	GDP	GDP

3.3.2. Drivers projections

This section presents the projections of the drivers listed in the preceding section, for the reference scenario. The time horizon of 2100 renders this exercise full of uncertainty but it is a necessary step in our analysis. Our main objective while choosing a reference scenario is to insure economic coherence in the choice of driver growths. In order to insure overall coherence in our projections, we have used the GEM-E3 World general dynamic equilibrium model. Though not specifically a projection tool[2], it ensures a global consistency in the macroeconomic development of countries and sectors, and therefore provides a coherent set of driver values (which are later used to derive the demands for energy services). A short description of the model is given in Appendix B. For this reference scenario, no fundamental disruptions are assumed but rather a continuation of historical tendencies. It must be clear however that our reference scenario represents only one of many possible futures, the overall uncertainty remaining very high.

3.3.2.1. Basic Assumptions

The GEM-E3 model requires exogenous assumptions on two sets of parameters: population growth and technical progress.

[2] But there are no valid projection models for such long horizons…

Population growth

Demographic evolution plays a crucial role in future development. The assumptions, reproduced in Table 7, are based on the DOE population projections till 2025 and on the B2-Message scenario after 2025. This gives a medium growth scenario, in which the population in the OECD countries declines from 2050 onwards but is still growing, though at a very low rate, in the rest of the World.

Table 7. Population growth rates assumptions

Region	**2010-2000**	**2020-2010**	**2030-2020**	**2040-2030**	**2050-2040**	**2060-2050**	**2070-2060**	**2080-2070**	**2090-2080**	**2100-2090**
Canada	0.72%	0.62%	0.44%	0.15%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
USA	0.85%	0.81%	0.68%	0.25%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
EU15	0.15%	0.03%	-0.03%	-0.05%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
Other European Countries	0.15%	0.03%	-0.03%	-0.05%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
Eastern Europe	-0.12%	-0.22%	-0.29%	-0.16%	-0.09%	-0.22%	-0.20%	-0.14%	-0.09%	-0.06%
Former Soviet Union	-0.24%	-0.22%	-0.29%	-0.16%	-0.09%	-0.22%	-0.20%	-0.14%	-0.09%	-0.06%
Australia & New Zealand	0.88%	0.70%	0.51%	0.18%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
Japan	0.08%	-0.19%	-0.32%	-0.17%	-0.09%	-0.12%	-0.14%	-0.12%	-0.08%	-0.07%
Central America	1.37%	1.00%	0.80%	1.04%	1.09%	0.82%	0.63%	0.47%	0.34%	0.23%
South America	1.34%	1.05%	0.89%	1.08%	1.09%	0.82%	0.63%	0.47%	0.34%	0.23%
South Mediterranean Countries	2.15%	1.90%	1.64%	1.40%	1.09%	0.82%	0.63%	0.47%	0.34%	0.23%
Africa	2.15%	1.90%	1.64%	1.40%	1.09%	0.82%	0.63%	0.47%	0.34%	0.23%
Middle East & Turkey	1.95%	1.73%	1.43%	1.31%	1.09%	0.82%	0.63%	0.47%	0.34%	0.23%
India	1.45%	1.12%	0.81%	0.64%	0.43%	0.23%	0.15%	0.10%	0.08%	0.06%
China	0.68%	0.46%	0.25%	0.40%	0.43%	0.23%	0.15%	0.10%	0.08%	0.06%
East South East Asia	1.08%	0.79%	0.61%	0.55%	0.43%	0.23%	0.15%	0.10%	0.08%	0.06%
Rest of Asia	1.67%	1.40%	1.09%	0.76%	0.43%	0.23%	0.15%	0.10%	0.08%	0.06%

The evolution sketched above implies a slow aging of the population. Moreover, economic development will induce an increasing urbanization in developing countries. Both tendencies will induce a decrease in the number of persons per household, which has been assumed for this scenario at 2% per year in all regions, the ageing being more important in the developed regions while the increased urbanization rate relates more to the developing regions.

Technical progress

For technical progress, the assumed evolution is in line with past trends. Labor productivity is increasing at a rate of 1.5% a year, slightly accelerating towards the end of the horizon, and partly compensating for the decline in the population growth. A gradual, though moderate shift in the production patterns is assumed towards services and away from the more energy intensive sectors. This trend is assumed to be more pronounced in the OECD countries. Energy savings are assumed to proceed at an average rate of 1% a year in all regions, reflecting the improvement in energy technology efficiency and the change in production technologies.

3.3.2.2. Drivers Projections from GEM-E3

As already mentioned, the drivers used in the TIMES model are the following:

- Population,
- Number of households,
- GDP,
- GDP per capita,
- Sectoral production, with a distinction made between energy intensive sectors (ferrous and non ferrous, chemicals and other energy intensive), other industries, and services.

All projections concern the annual growth rates of these drivers.

The figures for population and household growth rates were given in the previous section, as they are also an input for GEM-E3. The GDP growth is reproduced in Table 8, while the sectoral production growths are given in Table 9 in a more aggregated form (detailed projections for all regions are in Appendix A). The GDP growths are higher in the non-OECD countries, thus contributing to a certain convergence of the regional economies.

Table 8. GDP growth
(average annual growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	3.5%	4.1%	4.3%	4.0%	3.9%	3.7%	3.4%	3.0%
AUS	2.7%	1.8%	1.4%	1.3%	1.1%	1.2%	1.2%	1.3%
CAN	2.6%	1.9%	1.5%	1.5%	1.4%	1.4%	1.5%	1.6%
CSA	2.7%	2.8%	1.8%	1.8%	1.8%	1.8%	1.9%	2.0%
CHI	6.2%	4.8%	3.5%	3.6%	3.6%	3.2%	3.0%	2.9%
EEU	2.6%	1.9%	1.7%	1.1%	1.3%	1.3%	1.5%	1.7%
FSU	3.4%	2.6%	2.2%	1.5%	1.5%	1.5%	1.6%	1.8%
IND	4.4%	4.2%	3.6%	3.2%	3.0%	2.8%	2.7%	2.6%
JPN	1.1%	0.5%	0.4%	0.8%	0.9%	1.0%	1.1%	1.3%
MEX	2.8%	2.8%	2.0%	2.0%	2.0%	2.0%	2.1%	2.2%
MEA	3.6%	3.1%	2.7%	2.6%	2.6%	2.6%	2.6%	2.6%
ODA	3.7%	3.8%	3.9%	3.8%	3.5%	3.3%	3.1%	2.9%
SKO	3.8%	3.7%	3.6%	3.3%	3.3%	3.1%	3.0%	2.9%
USA	2.7%	2.0%	1.7%	1.5%	1.3%	1.3%	1.3%	1.4%
WEU	1.8%	1.0%	0.6%	0.7%	0.7%	0.7%	0.7%	0.3%

The sectoral growth pattern shows a shift away from energy intensive sectors and towards other industrial sectors and the service sectors, reflecting the assumption regarding the evolution of production technologies. Though it is more pronounced in the OECD countries, the same trend appears in the non-OECD countries by the end of the horizon.

Table 9. Sectoral production growth
(average annual growth rate)

Sector	Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
Energy intensive	Africa	3.5%	3.5%	3.9%	4.2%	3.9%	3.5%	3.4%	3.0%
Other industrial	Africa	3.6%	3.7%	4.1%	4.3%	3.9%	3.7%	3.8%	3.5%
Service	Africa	2.8%	3.2%	3.7%	4.0%	3.8%	3.6%	3.5%	3.4%
Energy intensive	Asia	4.1%	3.6%	3.2%	2.7%	2.4%	2.2%	2.2%	2.1%
Other industrial	Asia	3.7%	3.4%	3.4%	3.3%	2.9%	2.8%	3.0%	2.9%
Service	Asia	3.2%	3.0%	3.0%	2.8%	2.7%	2.6%	2.7%	2.7%
Energy intensive	Europe	1.2%	0.7%	0.2%	0.3%	0.0%	-0.2%	0.1%	0.2%
Other industrial	Europe	1.9%	1.5%	1.4%	1.3%	1.0%	0.9%	1.1%	1.2%
Service	Europe	1.6%	1.6%	1.7%	1.6%	1.4%	1.3%	1.4%	1.5%
Energy intensive	Latin America	3.0%	2.5%	2.6%	2.3%	1.8%	1.6%	1.7%	1.6%
Other industrial	Latin America	2.4%	2.2%	2.4%	2.3%	1.9%	1.8%	1.9%	1.9%
Service	Latin America	2.3%	2.1%	2.2%	2.1%	1.9%	1.8%	1.9%	2.0%
Energy intensive	North America	2.7%	2.1%	1.7%	1.6%	1.1%	0.8%	0.9%	0.7%
Other industrial	North America	2.4%	2.2%	2.1%	2.1%	1.8%	1.6%	1.7%	1.5%
Service	North America	2.5%	2.3%	2.4%	2.3%	2.1%	1.9%	2.0%	1.9%
Energy intensive	Pacific	1.0%	0.5%	-0.1%	-0.4%	-0.6%	-0.3%	0.0%	0.2%
Other industrial	Pacific	1.3%	0.8%	0.7%	0.8%	0.7%	0.7%	0.9%	1.0%
Service	Pacific	1.1%	1.0%	1.1%	1.0%	0.9%	1.1%	1.3%	1.5%

3.3.3. Elasticities of demands to drivers

The demands for energy services are linked to the drivers' projections via elasticities. These elasticities are meant to reflect changing patterns in energy service demands in relation to socio-economic growth, such as a saturation in some energy end-use demands, increased urbanization, or changes in consumption patterns once the basic needs are satisfied. The relationship between a demand and its driver is as follows:

$$\boldsymbol{demand(d,r,t) = driver(d,r,t)^{elasticity(d,r,t)}}$$

or equivalently, the following relationship between the growth rate of demand and the growth rate of its driver:

$$\frac{\delta\, \boldsymbol{demand}}{\boldsymbol{demand}} = \frac{\delta\, \boldsymbol{driver}}{\boldsymbol{driver}} \cdot \boldsymbol{elasticity} \qquad (1)$$

The elasticities chosen for this scenario are summarized in Table 10.

Table 10. Demand drivers and elasticities

Demand Category	**Driver**		**Driver Elasticity of Demands**		
			Before 2050		After 2050
Transportation demand	All regions		OECD	Non-OECD	All regions
Autos	GDPP		1.2	1.5	0.5
Buses	POP		0.7	0.8	0.8
Two/three wheelers	POP		0.7	0.7	0.7
Passengers rail transportation	POP		0.8	0.8	0.7
Domestic aviation	GDP		1.3	1.5	0.6
International aviation	GDP		1.3	1.5	0.6
Freight transport	GDP		1	1.2	0.4
Trucks	GDP		0.7	0.9	0.4
Freight rail transportation	GDP		1	1.2	0.4
Internal navigation	GDP		1	1.2	0.4
International navigation (bunkers)	GDP		1	1.2	0.4
Residential demand	All regions >2050	OECD < 2050			
Space heating	HOU	HOU	0.8	1/0.7*	0.5
Space cooling	HOU	GDPP	1	1	0.5
Hot water heating	POP	POP	1	1.1	0.8
Lighting	GDPP	GDPP	1	1.2	0.7
Cooking	POP	POP	0.7	0.8	0.5
Refrigerators and freezers	HOU	GDPP	1	1.2	0.8
Cloth washers	HOU	GDPP	1	1.2	0.8
Cloth dryers	HOU	GDPP	1	1.2	0.8
Dish washers	HOU	GDPP	1	1.2	0.8
Miscellaneous electric energy	GDPP	GDPP	1	1.2	0.8
Other energy uses	HOU	GDPP	1	1.2	0.8
Commercial demand	All regions				
Space heating	Service sector production		0.5	0.7/0.5*	0.3
Space cooling	Service sector production		0.8	0.8	0.4
Hot water heating	Service sector production		0.5	0.8	0.3
Lighting	Service sector production		0.8	1	0.4
Cooking	Service sector production		0.8	1	0.4
Refrigerators and freezers	Service sector production		0.8	0.8	0.4
Electric equipments	Service sector production		0.8	1	0.4
Other energy uses	Service sector production		0.5	0.8	0.4
Agriculture	Agriculture production		0.8	1	0.6
Industrial demand	All regions				
Iron and steel	Sectoral production (I)		0.7	1	0.5
Non ferrous metals	Sectoral production (I)		0.8	1	0.5
Chemicals	Sectoral production (I)		0.8	1	0.5
Pulp and paper	Sectoral production (O)		0.8	1	0.5
Non metal minerals	Sectoral production (O)		0.8	1	0.5
Other industries	Sectoral production (O)		0.8	1	0.6

HOU: # of households
POP: population
GDP: growth domestic product
GDPP: GDP per head
* Climate sensitive

The assumptions behind these figures are briefly described hereafter. Overall, it is assumed that in the long run, the developing regions are approaching the development patterns of the industrialized countries.

Passenger transport: there is a shift away from public transport towards private car with increasing income, with however a certain saturation level after 2050; the greater urbanization would also contribute to a lesser increase in the passenger-km demand.

Freight transport: accompanies more closely the growth of GDP, with a slight shift away from road transport before 2050. After 2050, it is assumed that congestion and a certain limit to globalization imposes a certain decoupling of the freight transport demand.

Residential demand: for the basic needs, the drivers are either the number of households or the population; for the other demand categories, the evolution of income is the dominant factor. In the long run, a certain saturation and changes in consumption patterns will lessen this link.

Commercial demand: follows the activity of the service sector, but with a decreasing link, in industrialized countries and also in developing countries after 2050.

Industrial and agriculture demand: the demand follows the sectoral production evolution but with a slight decoupling of this link after 2050 due to a greater efficiency in the production technologies, a shift towards more elaborated products and global markets maturity.

These assumptions are clearly disputable given the large uncertainty around the possible future development patterns, but this can only be addressed by looking at many different scenarios, which may be done by the model users in subsequent phases of the project.

3.3.4. Demand projections

As expressed by equation (1), a demand's growth rate projection is obtained by multiplying the growth rate of its driver by the demand elasticity. The evolution of demands is more contrasted between the OECD countries and the other regions before 2050 than after 2050, especially in the residential and the transport sectors because, besides the growth differentials, the elasticities are also higher in the non-OECD regions. After 2050 the evolution is more parallel because of the convergence in terms of growth rate and in terms of elasticities. Because of the large amount of data, the demand projections are provided only in electronic form (file *DMD_Proj.xls).*

3.3.5. Price elasticities of Demands

The reader will recall that a TIMES demand scenario takes the form of a set of *demand curves*, not just *demand projections*. The demand projections are exogenously fixed only in the reference scenario. For alternate scenarios, the demands may vary endogenously around the reference demands since they are elastic to their own prices (which are themselves determined within the model). To fully specify the demand curves, the user must therefore provide a set of own-price elasticities for all demand segments. The expression for a constant elasticity demand curve is:

$$\boldsymbol{ES/ES_0 = (p/p_0)^{pelasES}}$$

where
ES is a demand for some energy service;
ES_0 is the demand in the reference case;
p is the unit price of the energy service;
p_0 is the unit price in the reference case; and
$pelas_{PE}$ is the (negative) own-price elasticity of the demand.

In an alternate scenario that provokes an increase in demand prices, the demands will be affected downward, the more so if their elasticities are large and negative.

There are no comprehensive studies on the price elasticities of energy service demands, except for transport demands, but then they do not cover the whole world. Therefore, for this very long term analysis, expert opinion is used to estimate elasticities, based on energy demand price elasticities. The transition from the price elasticity of an *energy* demand to the price elasticity of the corresponding *energy service* demand, is based on some fundamental relationship between these two quantities.

First, energy demand is equal to energy service demand multiplied by the energy content of the process used to satisfy the demand.

$$\boldsymbol{ED = ES \bullet UE} \qquad (2)$$

where

ED: energy demand
ES: energy service demand
UE: energy demand per unit of energy service demand (a function of capital and energy).

Depending on the substitution possibilities between inputs and processes, the relationship between the two price elasticities will be different. We treat the two cases below.

a) Assuming a fixed relationship between capital and energy in the production function of energy services (Leontieff structure), then the price elasticity of energy demand is a function of the price elasticity of energy demand and the share of energy in the total cost:

$$\boldsymbol{pelas_{ED} = pelas_{ES} \bullet share\ of\ \ E\ \ in\ PES}$$

where *PES*: cost of the energy service

b) Assuming substitution possibilities between capital and energy in the production function (e.g. a Constant Elasticity of Substitution production function, or CES), then the price elasticity of energy demand will also depend on the substitution elasticity:

$$pelas_{ED} = pelas_{ES} * share\ of\ \ E\ in\ PES - \sigma(1 - share\ of\ \ E\ in\ PES)$$

where **σ** is the elasticity of substitution in the CES function.

The greater the share of energy cost in the total cost, the closer are the two elasticities, while the greater the substitution possibilities the greater the difference between the two elasticities.

Based on these relations and assumptions regarding the energy demand price elasticities and the substitution possibilities, energy services price elasticities were derived, and are reproduced in Table 11.

Table 11. Price elasticities of demands

DM			**DM**			**DM**			
Residential									
Heating/cooling/ hot water	EDelas	-0.45	cooking/ refrigerator	EDelas	-0.35	others	EDelas	-0.5	-0.5
	SUBelas	0.7		SUBelas	0.4		SUBelas	0.3	0.3
	Share EN	0.8		Share EN	0.8		Share EN	0.6	0.9
	ESelas	-0.39		ESelas	-0.34		ESelas	-0.63	-0.52
Commercial									
Heating/cooling/ hot water	EDelas	-0.55	cooking/ refrigerator	EDelas	-0.4	others	EDelas	-0.5	-0.5
	SUBelas	0.7		SUBelas	0.4		SUBelas	0.3	0.3
	Share EN	0.8		Share EN	0.8		Share EN	0.6	0.9
	ESelas	-0.51		ESelas	-0.40		ESelas	-0.63	-0.52
Industry									
energy intensive	EDelas	-0.7	other	EDelas	-0.4				
	SUBelas	1		SUBelas	0.4				
	Share EN	0.7		Share EN	0.8	depends on the cost included in MARKAL/TIMES			
	ESelas	-0.57		ESelas	-0.40				

In transportation there exist estimates of the price elasticity of the demand for transport, although they do not cover all the regions and are sometimes related to the cost of energy alone, and not to the total transport cost. Average figures for long term elasticities in OECD countries are given in Table 12.

Table 12. Price elasticities for transport demand

Passenger		Freight	
Private car	-0.7	Trucks	-0.9
Bus	-0.2	Train	-0.2
Train	-0.2	Ship	-0.2
Motorized two-wheelers	-0.3		
Ship	-0.1		
Air	-0.7		

For the non–OECD regions, these figures could be slightly lower in the first half of the horizon since the substitution possibilities are fewer.

4. Results

4.1. Scenarios

In this phase of the EFDA project, the only objective of model runs is to demonstrate the use of the model for a practical application. Therefore, the scenarios and results presented in this section should not be considered as the representation of a set of preferred reference or policy assumptions. The scenarios and results are therefore presented for demonstration purposes only. Two contrasted scenarios were selected, as described below.

4.1.1. Reference scenario

The reference scenario is the one described in section 3.2 and Appendix 1. It represents a situation with the following main characteristics:

Population growth is moderate during the entire century, with a marked slowdown after 2050. This corresponds to the assumptions of the IPCC B2 storyline.

GDP growth (as calculated by the GEM-E3 model) is strong, especially in less developed countries. There is a strong convergence in the developments of developed and less developed countries by the end of the century. This GDP growth structure is compatible with a continued globalization of the world economy, and with strong technical progress.

Biomass availability is large, and nuclear capacity is allowed to grow significantly over the horizon.

The evolution of the regional population and GDP is illustrated in Figure 7 and Figure 8.

4.1.2. Alternate scenario

The alternate scenario offers a strong contrast to the reference scenario. The only additional assumption of the alternate scenario is that a global CO2 tax is applied to all CO2 emissions from the entire, global energy system. The level of the tax rises linearly from $0/tonne CO2 in 2010 to $1000/tonne in 2100. It is thus equal to $10/tonne in 2010, $20/tonne in 2020 etc. As will be seen from the results, the alternate case imposes a strong constraint of the energy system, thereby inducing a decrease in energy service demands (and thus indirectly equivalent to a reduction of GDP), as well as decreases in several fuel demands, including electricity. These demand reductions are endogenously determined by the model.

4.1.3. Other scenario capability: specifying final fuel demands

The VEDA interface was enhanced in yet another way, to allow the direct specification of final fuel demands in the Industrial sector. In this mode, the user may specify trajectories for each industrial final energy form (oil products, electricity, gas, biomass, etc) instead of specifying demands for energy services. This feature may be quite useful if certain extreme industrial configurations must be tested, which would take awkward trial-and-error runs to achieve in the usual scenario mode. For instance, using this feature would make it easy to quickly check the consequences of a doubling (or halving) of industrial electricity demand in 2100 compared to the reference case.

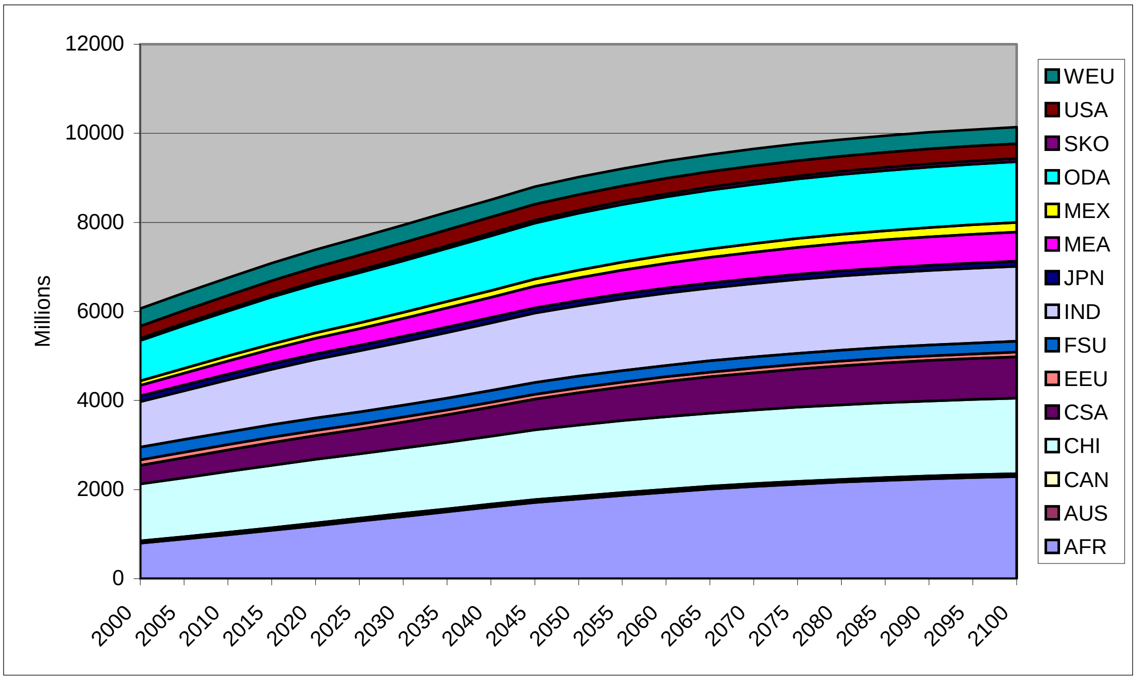


Figure 7. Population evolution in the BASE scenario

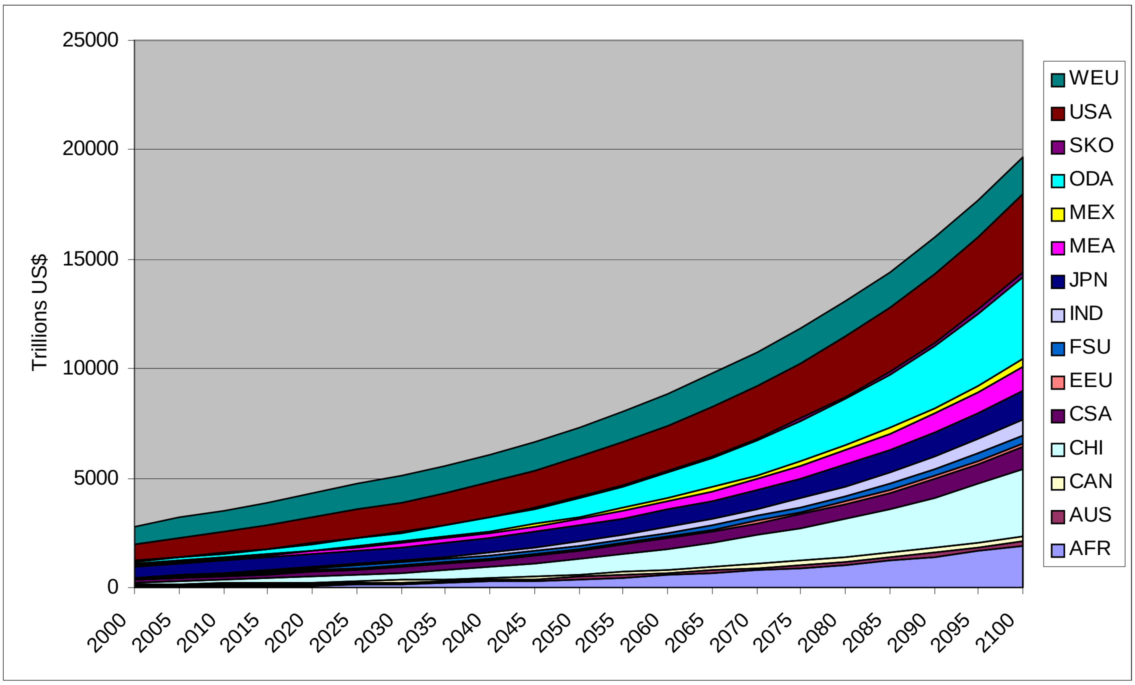


Figure 8. GDP evolution in the BASE scenario

4.2. *Results for the Base scenario*

4.2.1. Energy Extraction (Fossil and Biomass)

Figure 9 and Figure 10 show energy extraction by region and by type (coal, oil, gas, biomass), respectively. Among the large suppliers, Europe, South America, and Middle East see a marked slowdown after 2050. Other large suppliers (USA, China, etc.) show sustained growth

Figure 10 also shows that most of the increase comes from oil (a twofold increase over 100 years) and especially coal (fourfold increase over 100 years). Gas and Biomass more or less stagnate or experience small overall increases.

4.2.2. Electricity Production

Electricity production by type is shown in Figure 11. Coal fired plants and nuclear plants predominate in the later portion of the horizon. Gas and other plants play a fairly minor role throughout the period.

4.2.3. Energy consumption (Final Energy)

Figure 12 shows final energy by region. Here too, the overall growth slows down after 2050, with the notable exceptions of developing regions, transition economies, and the USA. Figure 13 shows energy consumption by the end-use sectors. The industrial and transportation sectors exhibit strong growth, whereas the commercial and residential sectors show moderate to low growth.

4.2.4. CO2 Emissions

Figure 14 shows total CO2 emissions by region, and Figure 15 shows emissions by sector. The regions with larger emission growth are those that showed larger growth of fossil energy (China, Asia, Africa, USA). The fastest growing emissions occur in the electricity sector, followed by the transportation and the industry sectors. The commercial and upstream emissions remain relatively small.

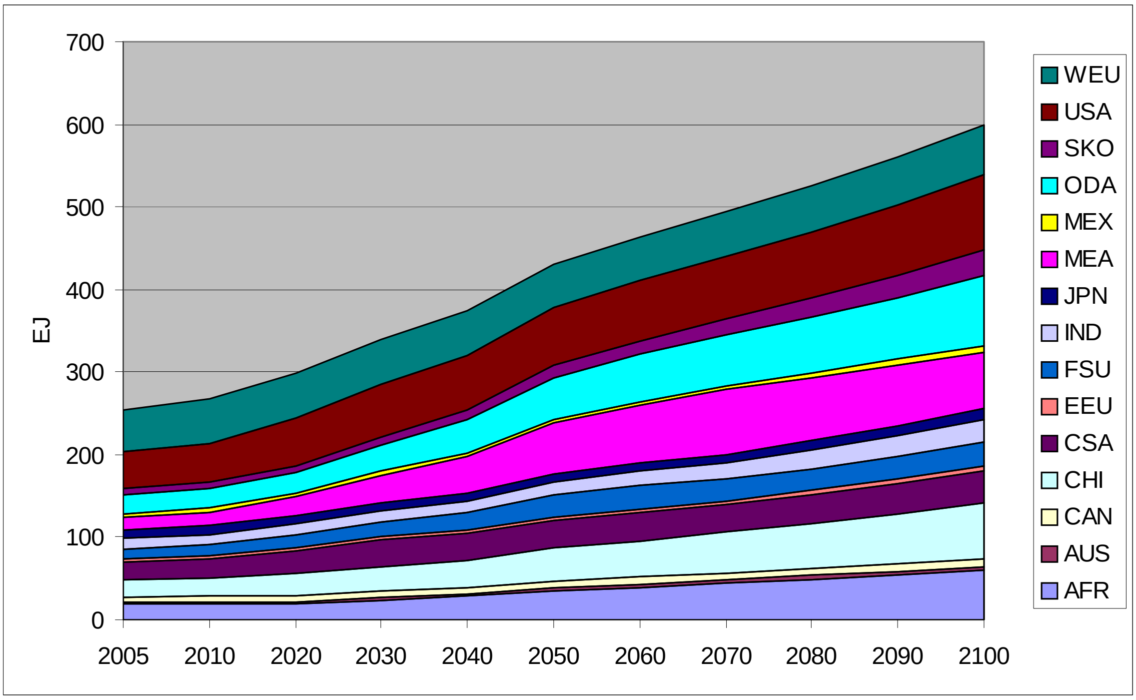


Figure 9. Energy extraction

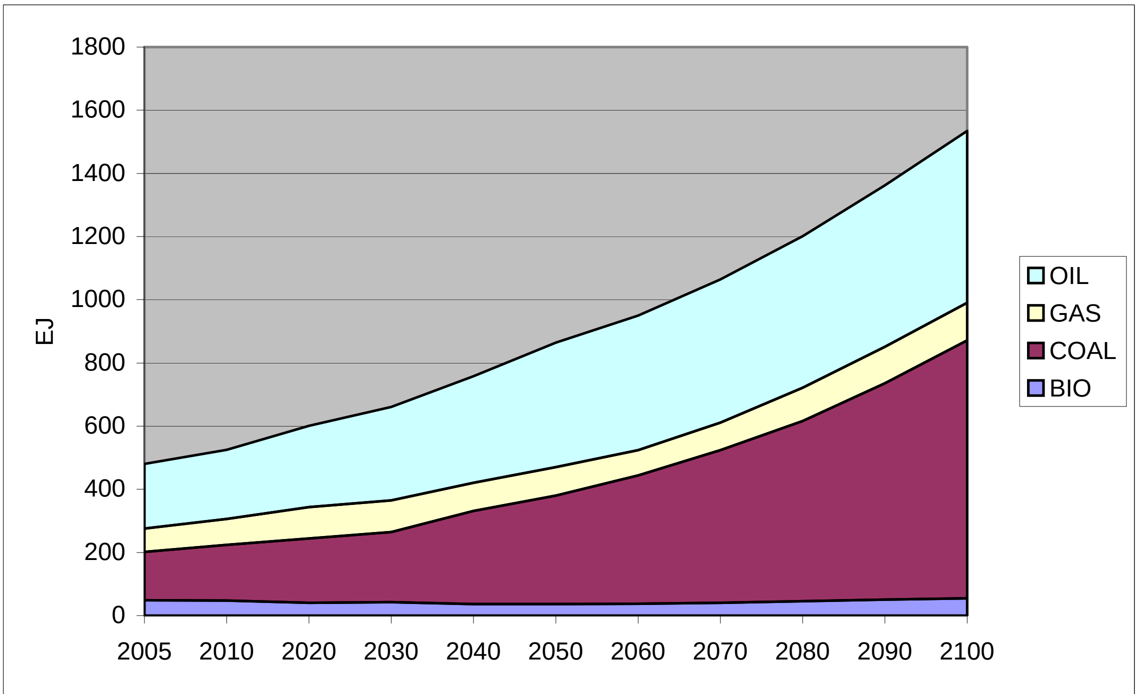


Figure 10. Primary energy by type

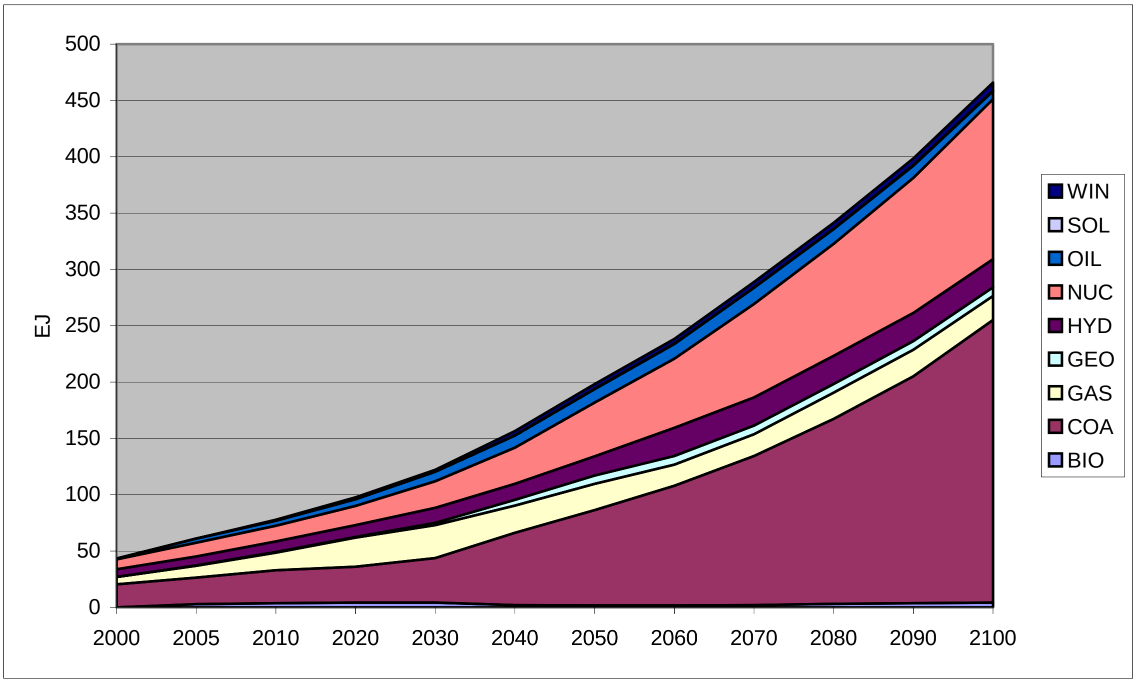


Figure 11. Electricity production by type

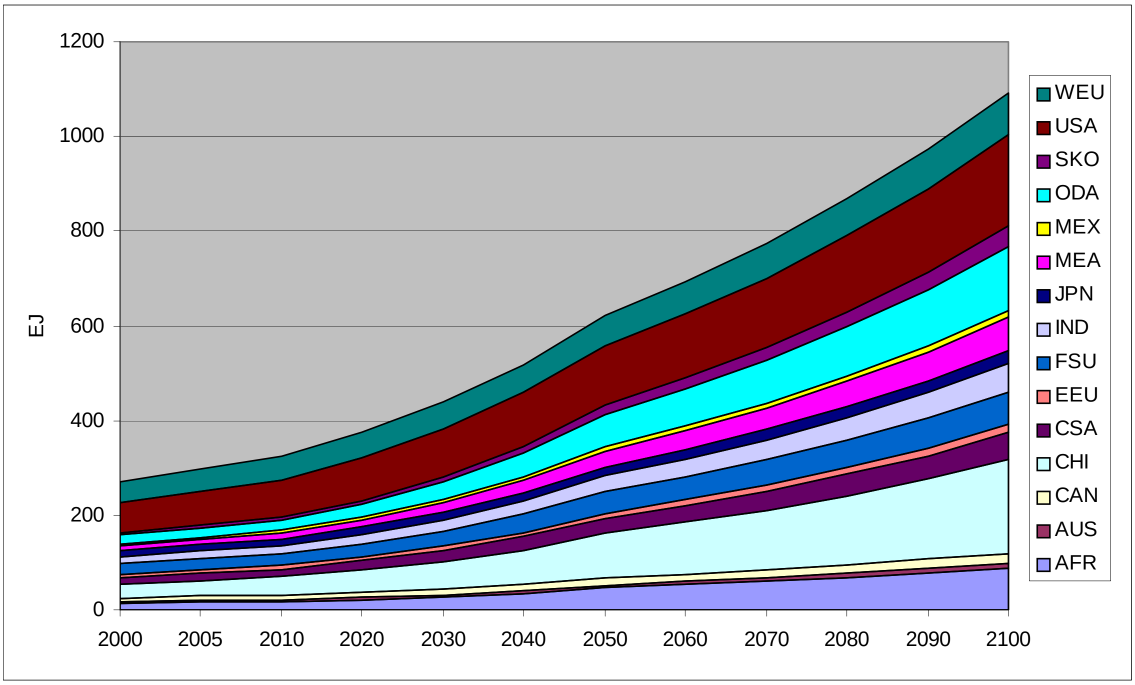


Figure 12. Final energy

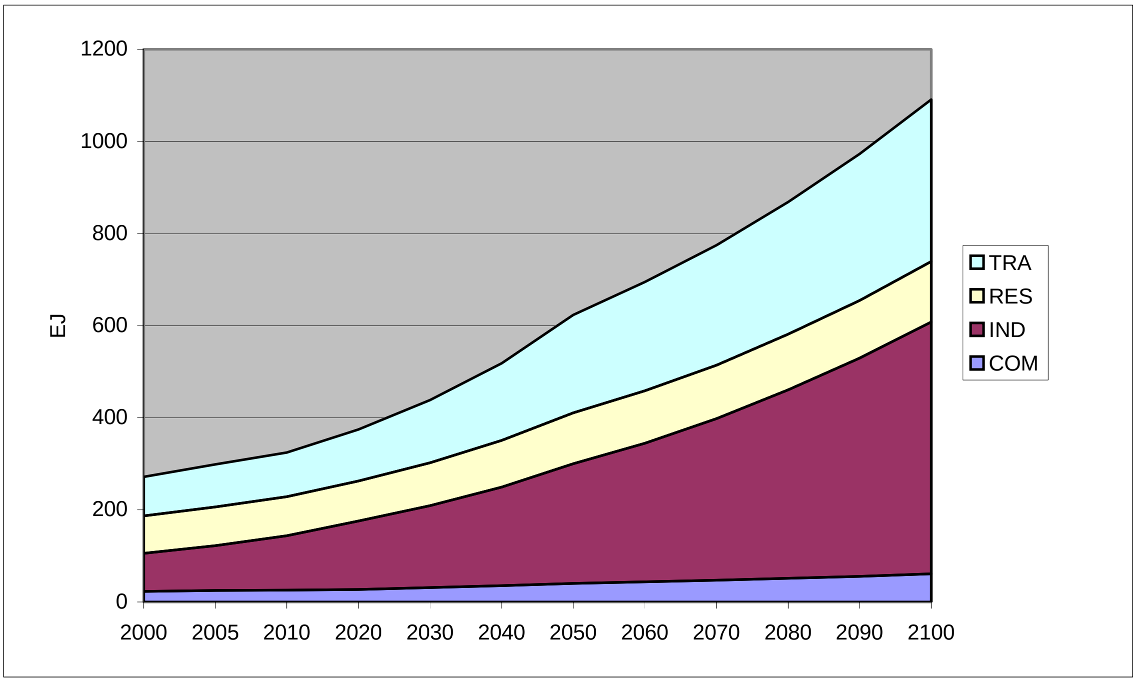


Figure 13. Final end-use energy

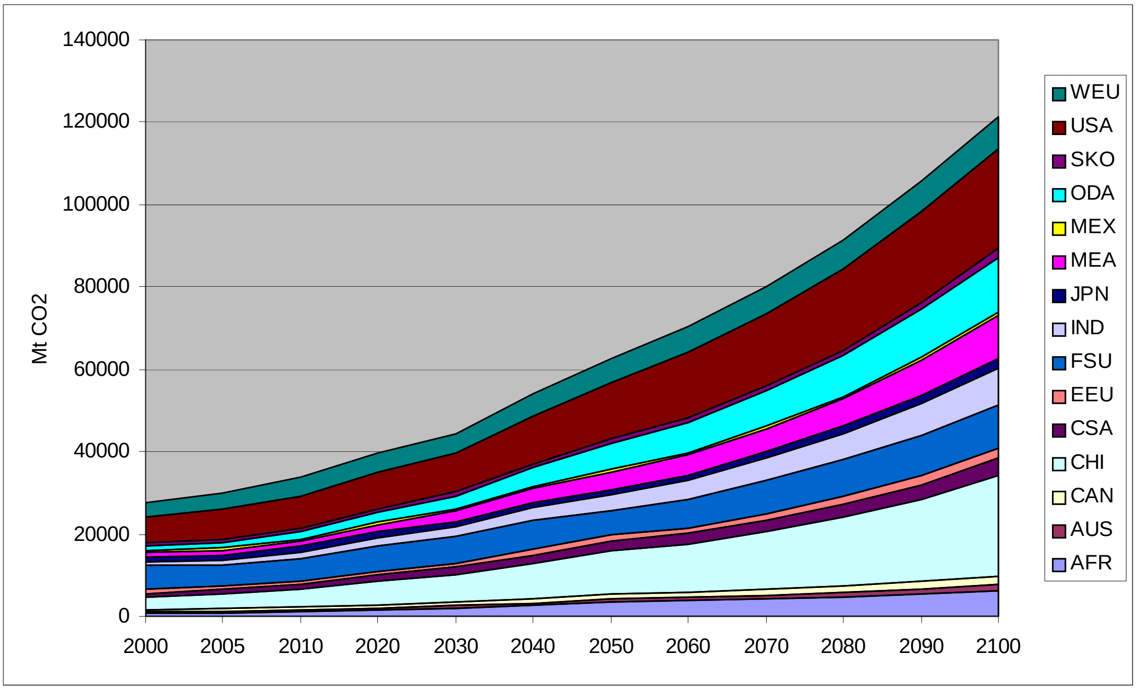


Figure 14. CO2 emissions by region

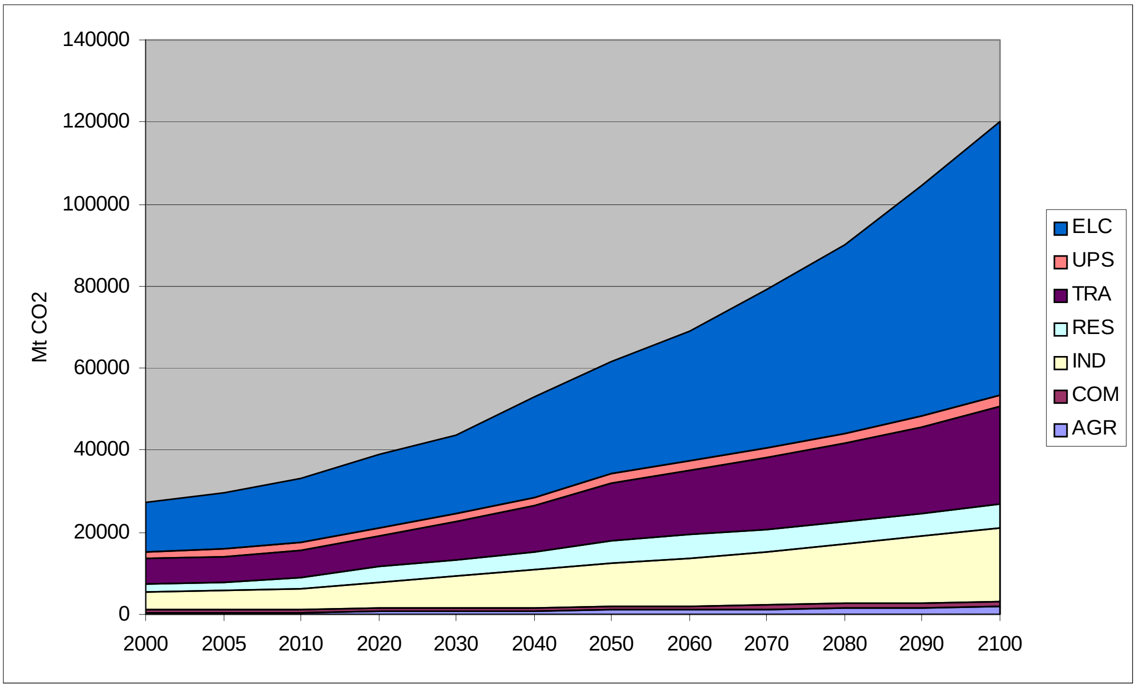


Figure 15. CO2 emissions by sector

4.3. Results for the CO2 tax scenario

In this section, we present and briefly discuss the impact of the imposition of a CO2 tax on the global energy system. We show below 7 figures illustrating this impact, successively treating: the total CO2 emissions (Figure 16), emissions from the electricity sector (Figure 17), and from other sectors (Figure 18 and Figure 19), and then a comparison of electricity production by type in the reference case (Figure 20) and in the alternate scenario (Figure 21). Figure 22 shows the relative growths of the three electricity types (renewables, fossil, nuclear) in the alternate scenario versus the reference one.

The main observations are as follows:

- Global CO2 emissions are reduced by 35% in 2050 and by 60% in 2100, compared to the Base case. This results in global emissions growing by less than 60% between 2000 and 2100 in the tax scenario, versus more than 300% in the reference scenario.
- The electricity sector's emissions are the most affected by the tax, a result that confirms many past studies. In our runs, the emissions from this sector are reduced by 89% in 2100, relative to the base case. Indeed, electricity sector emissions decrease by about 65% from 2000 to 2100, whereas they increase by close to 500% in the same period in the reference case.
- Emissions from other sectors are less dramatically affected than electricity sector emissions, but still significantly reduced in the industry and transport sectors. Industrial emissions are reduced by 36% in 2050 and 37% in 2100, transport emissions by only 7% in 2050 but 28% in 2100. Upstream emissions are less affected (-10% in 2050 and -–6% in 2100), and so are commercial emissions (-7% and –16%, respectively in 2050 and 2100). Residential sector emissions are almost the same in both scenarios.
- As expected, total electricity production is lower in the alternate scenario than in the reference scenario. The reduction is 7% in 2050, and 18 % in 2100. The electricity sector abandons coal and oil almost entirely by 2050, and replaces them by gas and nuclear, plus some renewables. In 2100, this substitution is even more pronounced, and coal is completely eliminated from the slate of fuels in the electricity sector. Figure 22 indicates that the amount of renewables used in the sector in 2100 in the alternate scenario, is 3 times the amount used in the reference case in the same year. Similarly, nuclear is 50% larger, while fossil fuels are 50% less.

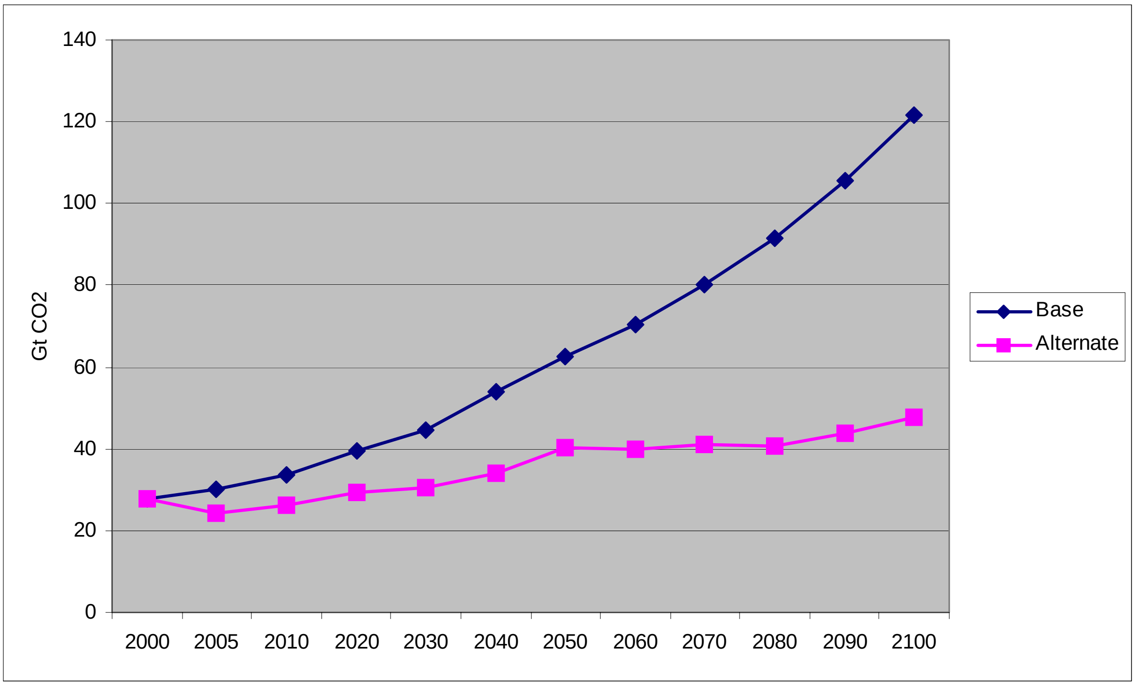


Figure 16. Total CO2 emissions

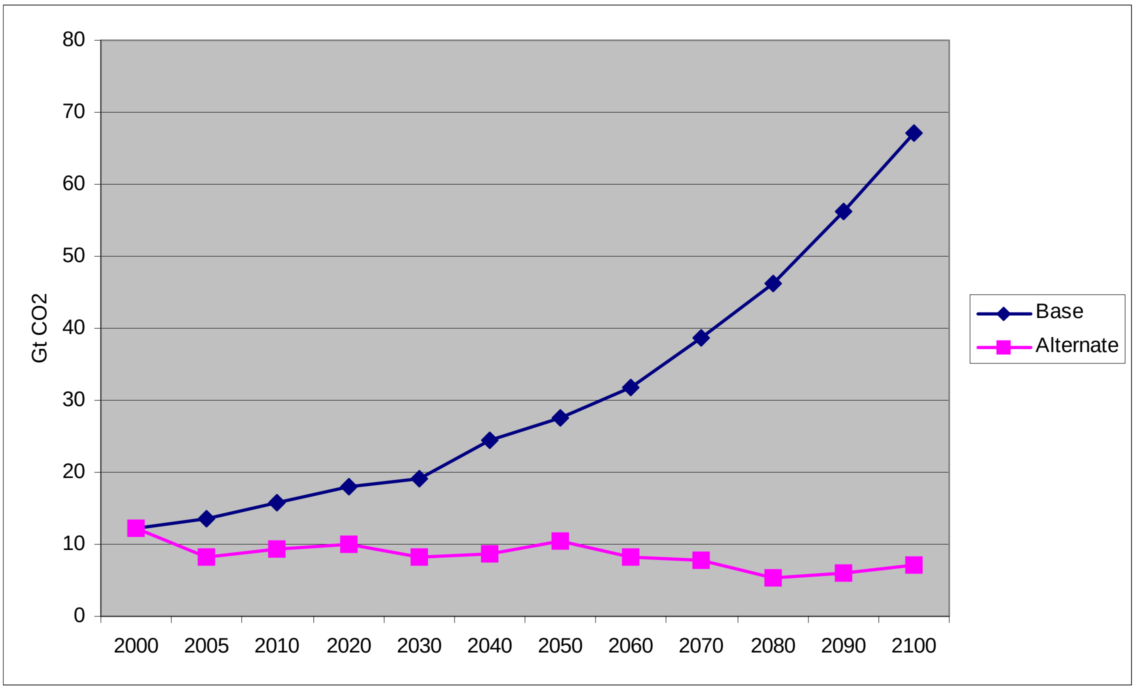


Figure 17. CO2 emissions from the electricity sector

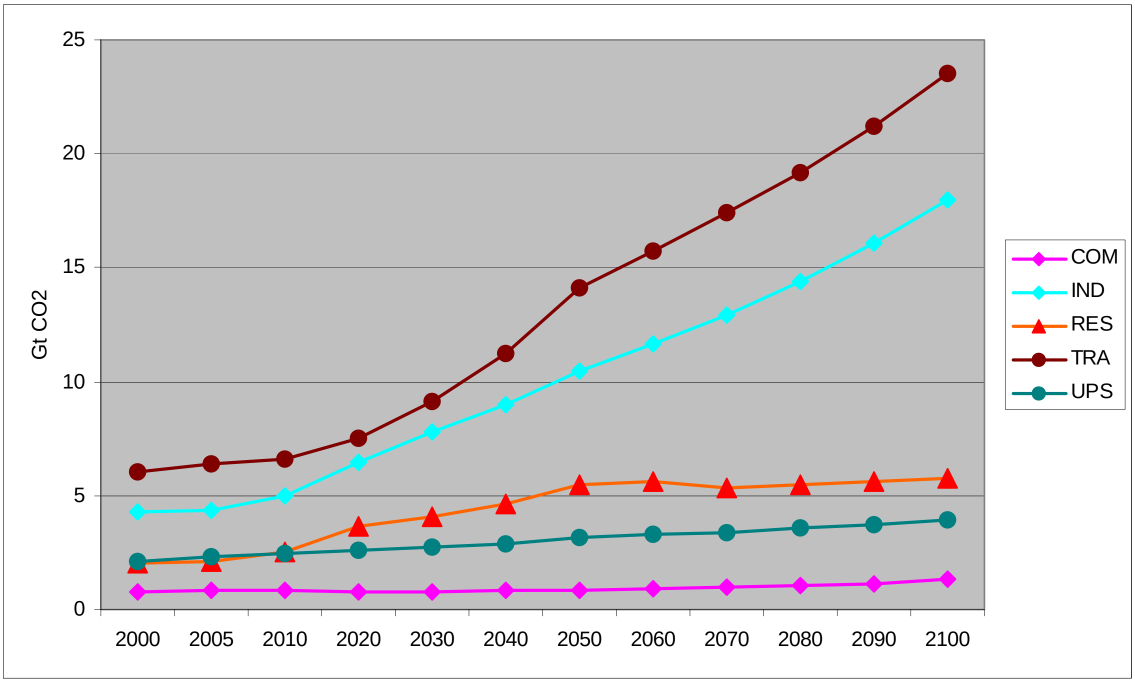


Figure 18. CO2 emissions from the other sectors: Base scenario

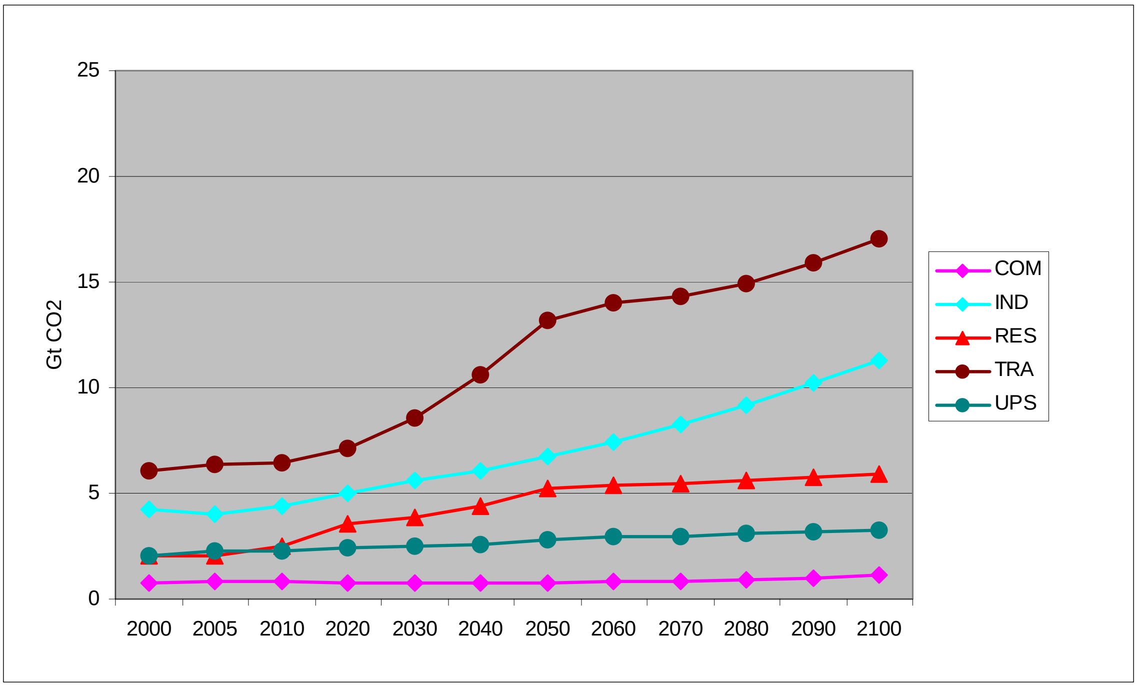


Figure 19. CO2 emissions from the other sectors: Alternate scenario

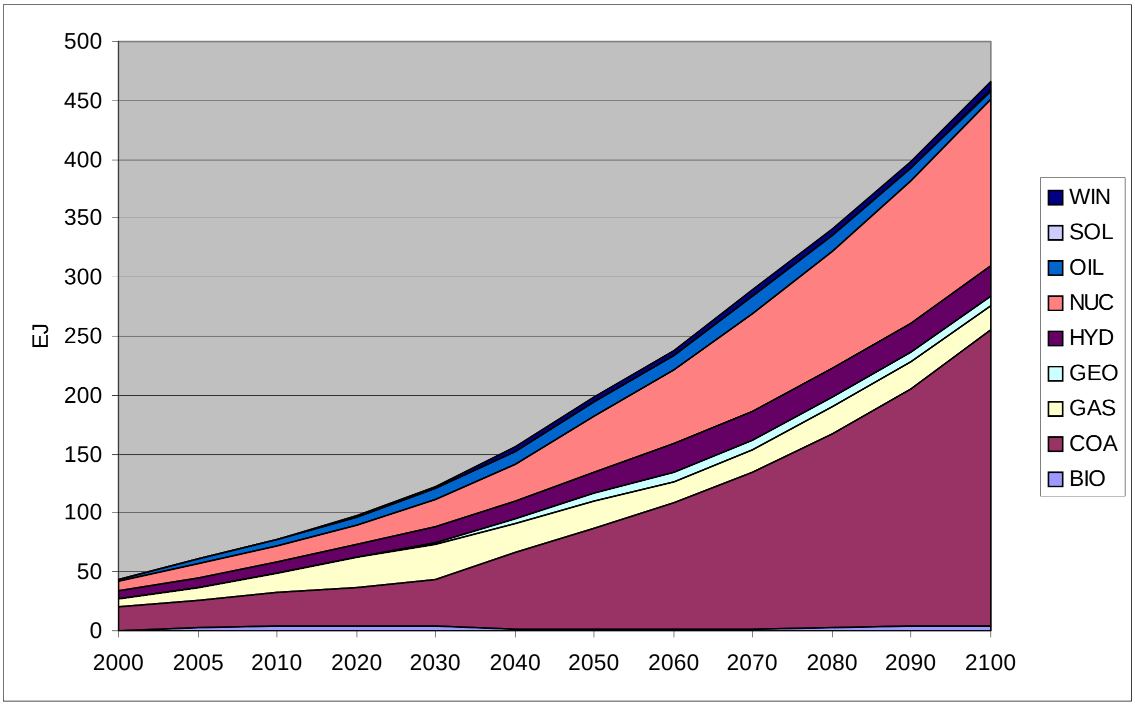


Figure 20. Electricity production in the reference scenario

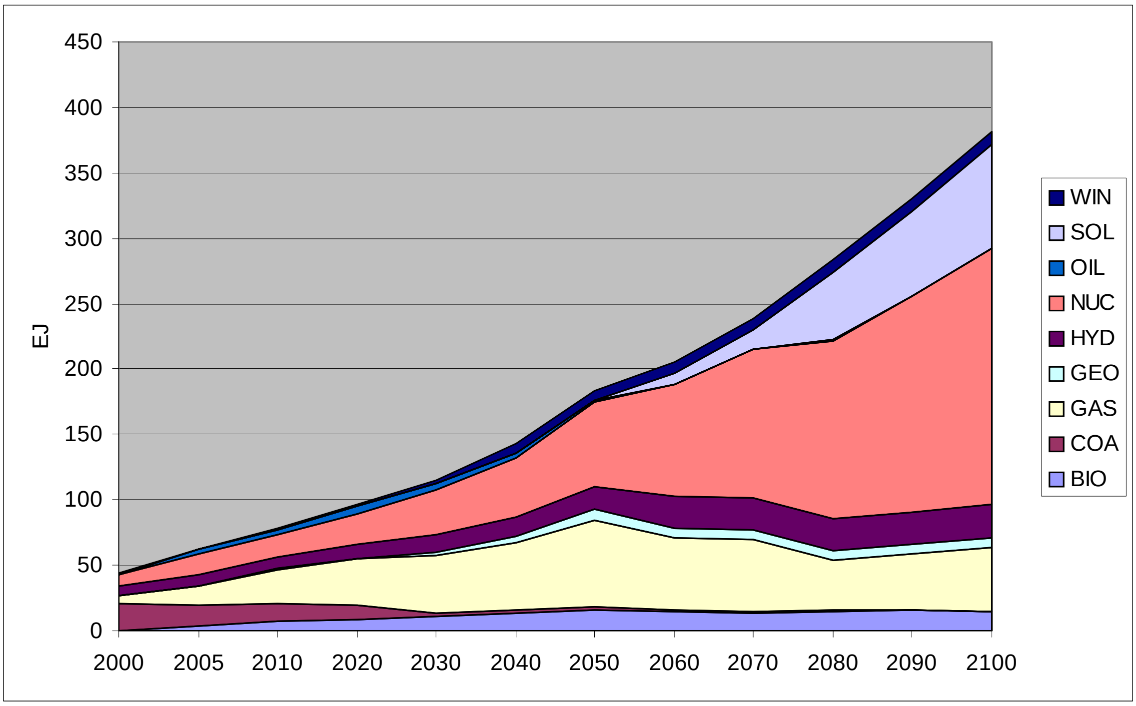


Figure 21. Electricity production in the alternate scenario

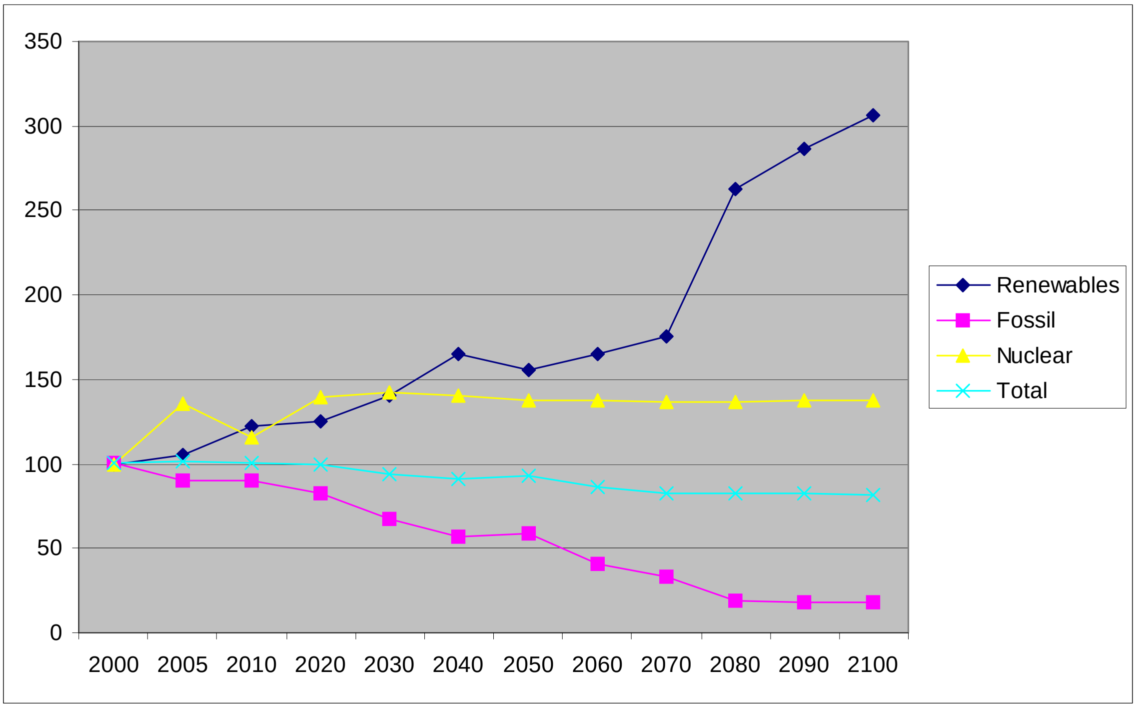


Figure 22. Relative importance of electricity types
(alternate / reference, index = 100 in 2000)

5. CONCLUSION

This report summarized three aspects of the EFDA World TIMES project. The first aspect concerns the description of the generic TIMES model developed by ETSAP and used for this project. A brief introduction to the model appears in section 2.1, and a more complete description in Annex 1. The second aspect relates to the software tools used for the user-friendly management of the model's inputs and outputs. These tools are based on the advanced versions of VEDA (front-end and back end) especially enhanced for this project. They are particularly adapted to the handling of very large, multi-regional databases as exist in the EFDA TIMES model. The two VEDA softwares are described in section 2.2, and the complete user's guides appear as annexes 4 and 5. The third aspect focuses on the particular implementation of TIMES satisfying the particular EFDA requirements. The EFDA model is described in section 3, and a more complete description of the EFDA Reference Energy System constitutes Annex 2. In order to illustrate the functioning of the model, two runs were conducted on two contrasted scenarios, and their results are presented in section 4.

This phase of the project would normally be followed by a more intensive utilization of the model to explore a variety of scenarios. Section 3 contains a general description of the scenario building process, but the creation of new scenarios would be adapted to the particular issues of interest to EFDA, whether they be of a technological or socio-economic nature. There is simply no limit to the variety of such scenarios. It is however our strong belief that scenarios should be constructed in a coherent and economically consistent manner, as discussed in section 3.

In summary, the value of this project would be greatly increased by a sustained utilization of the model. There is no doubt in our minds that during this process, many changes will be brought to the model, in the form of a more complete set of technologies, and more generally, the enhancement of the reference energy system. Our team is available for any further help it may provide in the future.

6. APPENDIX A: Sectoral GDP growth rates from the GEM-E3 baseline

The tables hereafter give the growth assumptions for the sectoral activity growth as derived from the GEM-E3 baseline. They give the average annual growth rate of the production of the sectors. Production includes value added, i.e. labor and capital input and material input.

Table 13. Agricultural production growth rates
(annual average growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	2.90%	3.81%	3.77%	3.35%	3.12%	2.83%	2.61%	2.42%
AUS	2.72%	1.99%	1.36%	1.25%	1.13%	1.18%	1.19%	1.23%
CAN	2.62%	1.98%	1.36%	1.26%	1.19%	1.26%	1.31%	1.45%
CSA	2.31%	2.12%	1.82%	1.82%	1.84%	1.89%	1.96%	2.10%
CHI	3.06%	1.99%	1.35%	2.04%	2.40%	2.23%	2.21%	2.26%
EEU	0.54%	1.48%	1.30%	1.02%	1.23%	1.25%	1.34%	1.56%
FSU	1.36%	1.27%	2.25%	1.50%	1.56%	1.63%	1.73%	1.94%
IND	4.02%	4.01%	3.57%	3.07%	2.84%	2.57%	2.44%	2.41%
JPN	0.85%	0.53%	0.22%	0.59%	0.76%	0.80%	0.83%	0.95%
MEX	2.56%	2.35%	2.02%	2.13%	2.20%	2.24%	2.30%	2.43%
MEA	3.68%	3.30%	2.71%	2.72%	2.67%	2.61%	2.56%	2.45%
ODA	2.97%	3.32%	3.54%	3.52%	3.38%	3.23%	3.08%	2.83%
SKO	2.71%	2.83%	2.72%	2.50%	2.52%	2.39%	2.33%	2.31%
USA	2.85%	1.90%	1.30%	1.04%	0.79%	0.77%	0.72%	0.69%
WEU	1.42%	1.01%	0.47%	0.60%	0.67%	0.66%	0.61%	0.55%

Table 14. Ferrous and non ferrous metals production growth rates
(annual average growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	3.54%	3.70%	3.67%	2.93%	2.36%	1.68%	1.01%	0.46%
AUS	3.00%	1.23%	0.09%	-0.19%	-0.54%	-0.50%	-0.43%	-0.20%
CAN	2.21%	0.87%	-0.19%	0.00%	-0.17%	-0.08%	0.01%	0.30%
CSA	3.04%	2.67%	1.50%	1.46%	1.29%	1.16%	1.09%	1.05%
CHI	5.04%	3.05%	1.12%	0.64%	0.65%	0.25%	0.15%	0.20%
EEU	-0.83%	-2.16%	2.19%	-0.66%	-0.30%	-0.39%	-0.16%	0.33%
FSU	2.04%	-0.74%	3.83%	0.18%	-0.22%	-0.54%	-0.53%	-0.12%
IND	4.26%	2.74%	1.40%	1.16%	1.01%	0.79%	0.78%	0.92%
JPN	0.64%	-0.65%	-1.36%	-0.58%	-0.35%	-0.33%	-0.31%	-0.20%
MEX	2.95%	2.71%	1.74%	1.69%	1.57%	1.48%	1.43%	1.39%
MEA	4.60%	3.64%	2.76%	2.50%	2.23%	2.04%	1.89%	1.60%
ODA	3.33%	2.65%	2.16%	1.86%	1.47%	1.16%	1.01%	0.92%
SKO	3.35%	3.09%	2.59%	2.20%	1.97%	1.57%	1.30%	0.95%
USA	2.50%	1.14%	0.54%	0.42%	0.09%	0.07%	0.04%	0.11%
WEU	0.93%	-0.41%	-1.12%	-0.61%	-0.44%	-0.43%	-0.47%	-0.59%

Table 15. Chemical production growth rates
(annual average growth rate)

Region	2010/	2020/	2030/	2040/	2050/	2060/	2070/	2100/

	2000	2010	2020	2030	2040	2050	2060	2070
AFR	3.68%	4.10%	4.22%	3.74%	3.53%	3.29%	3.03%	2.59%
AUS	2.86%	1.52%	0.86%	0.58%	0.30%	0.29%	0.30%	0.48%
CAN	2.72%	1.77%	1.06%	0.78%	0.52%	0.46%	0.46%	0.69%
CSA	2.89%	2.55%	1.89%	1.83%	1.75%	1.70%	1.68%	1.72%
CHI	5.30%	4.07%	3.34%	3.04%	3.20%	2.95%	2.86%	2.79%
EEU	0.16%	0.38%	2.26%	0.69%	0.87%	0.78%	0.85%	1.14%
FSU	2.07%	1.32%	4.30%	1.91%	1.79%	1.75%	1.76%	1.90%
IND	4.83%	3.87%	3.06%	2.51%	2.22%	1.92%	1.93%	2.23%
JPN	0.94%	0.07%	-0.54%	0.07%	0.30%	0.38%	0.46%	0.65%
MEX	3.54%	3.13%	2.39%	2.28%	2.22%	2.18%	2.16%	2.16%
MEA	4.78%	3.88%	3.19%	2.85%	2.59%	2.39%	2.22%	1.98%
ODA	4.14%	3.93%	3.88%	3.76%	3.49%	3.22%	2.99%	2.72%
SKO	3.28%	2.96%	2.71%	2.45%	2.39%	2.15%	2.01%	1.97%
USA	2.97%	2.00%	1.36%	1.04%	0.72%	0.69%	0.68%	0.81%
WEU	1.09%	0.27%	-0.26%	0.03%	0.19%	0.22%	0.20%	0.15%

Table 16. Other energy intensive sector production growth rates
(annual average growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	3.34%	3.72%	3.82%	3.34%	3.11%	2.81%	2.50%	2.22%
AUS	2.77%	1.19%	0.47%	0.25%	0.08%	0.14%	0.20%	0.38%
CAN	2.48%	1.13%	0.38%	0.29%	0.17%	0.24%	0.34%	0.70%
CSA	2.79%	2.28%	1.59%	1.55%	1.46%	1.40%	1.39%	1.46%
CHI	4.29%	2.18%	0.79%	1.32%	1.80%	1.79%	1.92%	2.20%
EEU	-0.12%	-0.01%	1.26%	0.36%	0.70%	0.68%	0.83%	1.18%
FSU	2.06%	0.92%	2.61%	1.09%	1.01%	0.93%	0.98%	1.23%
IND	4.20%	3.38%	2.47%	1.74%	1.31%	0.94%	1.04%	1.68%
JPN	0.79%	-0.23%	-0.42%	0.00%	0.22%	0.25%	0.29%	0.43%
MEX	2.86%	2.54%	1.99%	1.94%	1.92%	1.91%	1.91%	1.96%
MEA	4.45%	3.61%	2.96%	2.71%	2.52%	2.38%	2.26%	2.07%
ODA	3.48%	3.33%	3.21%	3.08%	2.79%	2.51%	2.35%	2.30%
SKO	2.94%	2.39%	1.82%	1.64%	1.65%	1.46%	1.45%	1.62%
USA	2.65%	1.65%	1.14%	0.96%	0.74%	0.74%	0.74%	0.83%
WEU	1.37%	0.29%	-0.19%	0.10%	0.23%	0.25%	0.24%	0.22%

Table 17. Other industries production growth rates
(annual average growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	3.56%	4.10%	3.94%	3.76%	3.64%	3.46%	3.23%	2.86%
AUS	2.47%	1.90%	1.55%	1.46%	1.32%	1.32%	1.33%	1.41%
CAN	2.49%	2.07%	1.76%	1.64%	1.46%	1.48%	1.48%	1.61%
CSA	2.31%	2.38%	1.88%	1.89%	1.88%	1.89%	1.92%	1.98%
CHI	4.45%	3.45%	2.40%	2.97%	3.17%	2.95%	2.87%	2.78%
EEU	1.94%	2.03%	1.38%	1.20%	1.41%	1.40%	1.50%	1.74%
FSU	3.44%	2.85%	1.85%	1.62%	1.60%	1.58%	1.60%	1.70%
IND	4.00%	3.81%	3.13%	2.92%	2.78%	2.56%	2.47%	2.44%
JPN	1.17%	0.57%	0.66%	0.80%	0.97%	1.02%	1.07%	1.21%
MEX	2.58%	2.61%	2.10%	2.04%	2.02%	2.03%	2.03%	2.03%
MEA	3.61%	3.13%	2.82%	2.76%	2.68%	2.63%	2.60%	2.55%
ODA	3.09%	3.33%	3.39%	3.28%	3.02%	2.78%	2.61%	2.49%
SKO	3.29%	3.40%	3.13%	2.98%	2.94%	2.78%	2.67%	2.55%
USA	2.42%	2.14%	1.84%	1.70%	1.50%	1.49%	1.48%	1.54%
WEU	1.78%	1.25%	0.87%	1.03%	1.11%	1.13%	1.14%	1.19%

Table 18. Service sector production growth rates
(annual average growth rate)

Region	2010/ 2000	2020/ 2010	2030/ 2020	2040/ 2030	2050/ 2040	2060/ 2050	2070/ 2060	2100/ 2070
AFR	2.75%	3.60%	3.78%	3.60%	3.58%	3.47%	3.28%	2.84%
AUS	2.39%	2.19%	1.86%	1.81%	1.72%	1.76%	1.78%	1.89%
CAN	2.34%	2.26%	1.92%	1.90%	1.86%	1.90%	1.93%	2.06%
CSA	2.22%	2.15%	1.87%	1.90%	1.94%	2.01%	2.10%	2.27%
CHI	3.86%	2.96%	2.02%	2.37%	2.66%	2.44%	2.40%	2.46%
EEU	0.51%	1.47%	1.41%	1.33%	1.56%	1.58%	1.70%	1.94%
FSU	1.95%	2.11%	2.09%	1.60%	1.67%	1.73%	1.82%	2.02%
IND	3.37%	3.37%	2.81%	2.68%	2.59%	2.41%	2.35%	2.34%
JPN	0.93%	0.96%	0.80%	1.24%	1.45%	1.53%	1.61%	1.78%
MEX	2.40%	2.27%	2.01%	2.04%	2.10%	2.18%	2.26%	2.41%
MEA	3.19%	3.21%	2.99%	2.99%	3.02%	3.06%	3.10%	3.14%
ODA	2.74%	3.07%	3.12%	3.11%	2.92%	2.70%	2.55%	2.43%
SKO	2.67%	2.89%	2.93%	2.78%	2.82%	2.74%	2.69%	2.65%
USA	2.53%	2.41%	2.10%	2.00%	1.87%	1.89%	1.91%	2.01%
WEU	1.66%	1.67%	1.35%	1.45%	1.54%	1.59%	1.62%	1.73%

7. APPENDIX B: GEM-E3, A Computable General Equilibrium Model for studying Economy-Energy-Environment Interactions[3]

7.1. Overall description of the model

The GEM-E3 model is an applied general equilibrium model, simultaneously representing World regions or EU countries, linked through endogenous bilateral trade. It aims at covering the interactions between the economy, the energy system and the environment. The model computes simultaneously the competitive market equilibrium under the Walras law and determines the optimum balance for energy demand/supply and emission/abatement. A major aim of GEM-E3 in supporting policy analysis is the consistent evaluation of distributional effects, across countries, economic sectors and agents. The burden sharing aspects of policy, such as for example energy supply and environmental protection constraints are fully analyzed, while ensuring that the European/World economy remains at a general equilibrium condition.
The model has the following general features:

It scope is general in two terms: it includes all simultaneously interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agent's behavior.
It formulates separately the supply or demand behavior of the economic agents which are considered to optimize individually their objective while market derived prices guarantee global equilibrium
It considers explicitly the market clearing mechanism and the related price formation in the energy, environment and economy markets: prices are computed by the model as a result of supply and demand interactions in the markets and different market clearing mechanisms, in addition to perfect competition, are allowed
The model is simultaneously multinational (for the EU or the World) and specific for each country/region; appropriate markets clear European/World wide, while country/region-specific policies and distributional analysis are supported
Although global, the model exhibits a sufficient degree of disaggregation concerning sectors, structural features of energy/environment and policy-oriented instruments (e.g. taxation). The model formulates production technologies in an endogenous manner allowing for price-driven derivation of all intermediate

[3] The GEM-E3 model was built under the auspices of European Commission (DG-RES) by a consortium involving principally NTUA, KUL, ZEW and ERASME.

consumptions and the services from capital and labor. For the demand-side the model formulates consumer behavior and distinguishes between durable (equipment) and consumable goods and services. The model is dynamic driven by accumulation of capital and equipment. Technology progress is explicitly represented in the production functions and for each production factor.
The model formulates pollution permits for atmospheric pollutants and flexibility instruments allowing for a variety options, including: allocation (grandfathering, auctioneering, etc.), user-defined bubbles for traders, various systems of exemptions, various systems for revenue recycling, etc.

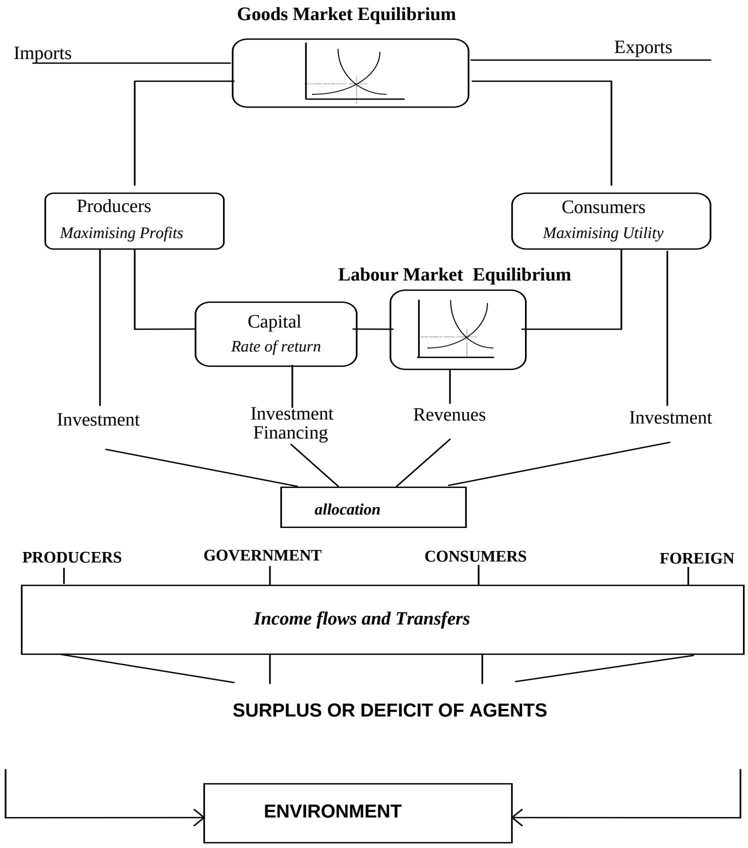


Figure 23. Basic scheme of the GEM-E3 model

Figure 23 above gives the basic scheme of the model.

7.2. The current operational versions of the model

There are two versions of GEM-E3, GEM-E3 EUROPE and GEM-WORLD. They differ in their geographical and sectoral coverage, but the model specification is the same. They use the GAMS software and are written as a mixed non-linear complementarity problem solved by using the PATH algorithm.

7.3. The Geographical Aggregation

7.3.1. The World version of GEM-E3

The model uses the GTAP-4 database and the IEA energy statistics. The base year is 1995. The GTAP database includes more than 50 world regions, which have been aggregated into 18 regions. The model code allows however for a user-defined aggregation of regions and definition of the regional coverage of the model. The 18 regions are: Australia and New Zealand, Japan, China, India, Rapid growing Asian countries, Rest of Asia, USA, Canada, Central America, South America, EU15 countries, Other European countries, Central European Associates, Former Soviet Union, Mediterranean countries, Middle East, Africa, Rest of the World.

7.3.2. The European version of GEM-E3

The European version covers 14 EU countries and the ROW (in a reduced form) and is based on the EUROSTAT database (IO tables and National Accounts data). The base year is also 1995.

7.4. The sectoral disaggregation level

The model distinguishes 18 productive branches:

- **Agriculture**.
- **Energy**: solid fuels, crude oil & refined oil products, gas, electricity.
- **Manufactured goods**: ferrous and non ferrous ore/metals, chemical products, other energy intensive goods, electric goods, transport equipment, other equipment goods, consumer goods, building and construction (in the World version, consumer goods are further disaggregated into food, textile and other products).
- **Services**: telecommunications, transport, credit and insurance, other market services, non market services (the World version has only two market services, trade & transport and other market services).

The database of the World model includes more than 50 production branches. The model code allows for a user-defined aggregation of branches and traded products.

7.5. The Model specification

7.5.1. The domestic producer's behavior

7.5.1.1. Domestic production

For each branch, domestic production is represented through a nested separability scheme involving capital, labor, electricity, fuels and materials. Fuels are further divided in coal, gas and oil and materials in fourteen categories of inputs.

First, production is split into two aggregates, one consisting of capital stock and the other aggregating labor, materials, electricity and fuels. Further down, the aggregate is first split into electricity and the other inputs, then the other inputs into labor, materials and fuels, the ensuing production functions are further divided in their components parts. The CES specification, with factor augmenting technical change, is used throughout. It allows also a coherent representation of the branch reaction (e.g. production factor switching or emission abatement) towards the use of environmental instruments, such as tradable permits, environmental taxation or standards. The model uses dual unit cost functions to represent the supply behavior of the producers and derives factor demand by means of the Shephard lemma.

7.5.1.2. Investment demand

The desired demand for capital, which fixes the investment demand of the firms, is determined through their optimal decision on factor inputs. The assumptions regarding the expectations of producers on future prices, interest rate and growth of the economy are important for the dynamic characteristics of the model. As the stock of capital is fixed within the year in GEM-E3, the investment decision of the firms affects their production frontier only the next year.

7.5.2. The consumer's behavior

The household behavior is represented by an intertemporal model of the household sector. In a first stage the household decides each year on the allocation of its resources between present and future consumption of goods and leisure. This decision is modeled as the maximization of an intertemporal utility function under a life-time resource constraint, using a LES formulation. It derives the saving and consumption by households and their labor supply.

In a second step, the household allocates its consumption between durable goods and non-durables, again through a LES scheme. The categories of goods considered in the model are:
non durables: food, beverages & tobacco, fuel and power, housing, house furniture, purchased transport, operation of transport, clothing, medical and health expenditure, communication, recreation, entertainment, other services
durables: cars, heating systems, electric appliances

Special care is given to the treatment of durable goods by explicitly linking the consumption of specific non durables to the stock of durable. The price of the durable used in the consumption decision thus reflects not only the market price of the durable but also the price of the non durables linked to the durable. It can also incorporate the cost for the consumer of environmental policies.

7.5.3. The government

Government final demand by product is obtained by applying fixed coefficients to the exogenous volume of government consumption and investment.

The model distinguishes 9 categories of receipts: indirect taxes (mainly excises), value added taxes, production subsidies, environmental taxes, social security contributions and transfers, import duties, foreign transfers and revenue from government firms.

7.5.4. The rest of the world

As the European model does not cover the whole planet, the behavior of the rest of the world is exogenous: imports demanded by the ROW depend on the price offered by the exporters from the European Union and exports from the ROW to the European Union, i.e. the supply of the ROW, occur at a fix price. For the World model, all behavior are endogenous.

7.5.5. Aggregate domestic demand

The specification of the model assumes further that the total domestic demand by branch (from household, producers and government) can be satisfied either by domestically produced goods either by imported goods, though they are not considered perfect substitutes. This allocation occurs through the minimization of the buyer’s total cost, following the Armington type formulation. The price used in the demand function is the ‘composite’ good price, a function of the supply price of the domestically produced goods and the price of the imported goods.

The total imports by branch are, at a second level, allocated over the countries of origin according to the relative import prices. The EU countries/World regions buy imports at the prices set by the supplying countries following their export supply behavior.
The model computes, for each branch and for each EU country/World region, the imports from and the exports to each EU country/World region and to the ROW in the form of a trade matrix.

7.5.6. Equilibrium on the good and labor markets

In the goods market a distinction is made between tradable and non tradable goods. For the tradable goods the equilibrium condition refers to the equality between the supply of the composite good, related to the Armington equation, and the domestic demand for the composite good. The equilibrium condition assumes at this stage perfect competition on the good markets.

For the non tradable, there is no Armington assumption and so the good is homogenous. The equilibrium condition serves then to determine domestic production, the supply behavior being modeled through the supply price equation.

For the labor market, at this stage it is assumed that wage are flexible such as to ensure full employment. On the demand side we have the labor demand by firms (derived from their production behavior) and on the supply side we have the total available time resources of the households minus their desire for leisure (derived from the maximization of their utility function). The equilibrium condition serves to compute the wage rate. Another version of GEM-E3 allows wage-rigidity and hence the possibility of unemployment.

7.5.7. The income account

The income flows in the real sector of the model are grouped within the framework of a Social Accounting Matrix, which ensures consistency and equilibrium of flows from production to the agents and back to consumption.

Equilibrium, in quantity and in value, on the good and labor market is guaranteed by the price formation mechanism on these markets.

7.5.8. Evaluation of externalities

The model evaluates the energy-related emissions of CO_2, NOx, SO_2, VOC and PM as a function of the energy consumption and the abatement level per branch and per pollutant. These emissions are then translated into concentration/deposition of pollutants, taking into account the transportation (between countries) and transformation mechanism of pollutants. In a final step, the damage generated by these concentration/deposition of pollutants are computed in physical units and valued through valuation function.

Three types of instruments are formulated: taxes, tradable pollution permits, and emission standards (upper bounds on sectors and/or countries). A variety of policy institutional regimes associated to these instruments are considered (burden sharing rules, limits on trade, recycling mechanism). The possibility for market power in permit markets is also modeled.