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Report on model updating and enhancing

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Table of Contents

1. Introduction 2
2. Models overview 3
3. WITCH (FEEM) 7
4. TIAMEC (ECN) 18
5. TIAM (KANLO) 22
6. PEM-TEAMS (USTUTT) 55
7. DEMETER (UNIMAN) 56
8. GEMINI-E3 (ORDECYS) 57

1. Introduction

The goal of this deliverable is to report on the improvements made by each integrated assessment modeling team in terms of better specification of the model, more recent updating, and overall model enhancements. This effort is meant to prepare the models for the numerical analysis of WP2,5,6 and 7.

The deliverable is structured as follows: Section 2 reports a questionnaire that provides a general overlook of the modeling suite and of the most important modeling advancements made by each group. The table also serves the purposes of confronting the different modeling architectures. Following sections (3 to 8) report on the enhancements included in each model.

2. Models overview

To begin with, a questionnaire was circulated among modeling teams to gather the main information regarding the structure of the different models.

Model Name	**DEMETER (UNIMAN)**	**GEMINI-E3 (ORDECSYS)**	**PEM / TEAMS (USTUTT)**	**TIAM (KANLO)**	**TIAMEC (ECN)**	**WITCH (FEEM)**
Model Type	Global E3 optimal growth model	Top down, CGE model	Bottom Up	Technology BU, with price-elastic demands	Bottom up, linear optimization, social planner	Top down, optimal growth, fully dynamic
Geographical coverage	One world region	World 28 regions	EU-27 + Switzerland, Norway, Iceland	World, 15 regions	Global (15 regions)	World. 12 regions
Energy sector description, link with economic activity	2 energy sources 1. Fossil fuels 1b. FF complemented with CCS 2. Non-fossil fuel energy	5 energy fuels/sectors : coal, crude oil, refined oil products, natural gas, electricity	Public and Autoproducer, Electricity and Heat, hard link with end use demand	Very detailed technological descriotion. Link with economy via a) own price elasticities of demands fro energy services, and b) linkage with CGE model (GEMINI-E3)	A technologically rich description of the energy sector, including all relevant technologies. Link to economy only through demand elasticities	7 power generation technologies, 5 fuels. Hard linked with economy.
Timescale, calibration year	Calibration 2005. Timescale: 2010-2200	To 2050, one year timesteps, Calibrated at 2001	2000 - 2030 5 year steps, and 2040, 2050, 12 time slices all periods	2005-2100 Base year=2005	Until 2100, calibrated for 2005	To 2200, 5 years timesteps Calibrated at 2005
MACROECONOMIC DRIVERS						
Population exogenous / endogenous? Source	Exogenous	Exogenous. UN projection, median scenario	exogenous	Exo, source=IPCC scenario B2	Exogenous	Exogenous. UN2004 medium variant
GDP exogenous /endogenous?	Endogenous	Endogenous	exogenous	Exogenous (from GEMINI-E3)	Exogenous	Endogenous
If endogenous, what is the growth engine – what are the exogenous drivers except demography?	Main productivity growth exogenous Capital stock endogenous. Energy Productivity endogenous	Exogenous : Total factor productivity growth (on labor and energy)				Investments in different types of capital stocks, Investments in R&D, Exogenous total factor productivity growth.
PPP or/and MER value? Benchmark year?	NA	MER US$2001		MER		MER US$2005
TRADE						
Fuels	NA	Traded : Armington Assumption	Electricity	All	Coal, crude oil, gas, LNG	Not active in basic version
Other goods	NA	Traded : Armington Assumption	no trade	Energy services (42) GHG emissions (3)		No trade in other goods. Spillovers in knowledge capital
Permits	NA	Trade in carbon permits, given an initial allocation	Carbon permit, green and white certificate trade	GHG (3 gases) or CO2 alone	Trade of GHG permits	Trade in carbon permits. Given an initial

			with given initial allocation (per sector and technology) Price of permit = shadow price of commodity			allocation of permits the price is defined through a tâtonnement process. Banking of permits for future use.
FOSSIL RESOURCES						
OIL, GAS, COAL, URANIUM: What drives the dynamics of these sector (price, reserves, rule of behavior of some producers)?	No exhaustion modelled. Fossil fuel base incl. coal assumed sufficiently large	Computed on the basis of energy prices projection Uranium not described	potentials and prices of resources exogenous per region	Reserves, prices, extraction costs. OPEC behaviour is modelled via control of their production levels	Resources divided into several categories based on their availability (existing, enhanced recovery, new discovery) and resource type (e.g. oil sands, heavy oil etc). These are further divided to several cost categories.	Price of resources depends on cumulative world extraction (endogenous)
TECHNICAL CHANGE AND OPTIONS TO DECARBONIZE THE ECONOMY						
Detailed description of TC : - TFP / labor productivity - Energy efficiency and carbon intensity - which technologies are subject to ITC ?	- Exogenous Hicks neutral TC for final good - energy savings possible through shift along exogenous iso-output curve - LbD CCS and Non-FF	TFP Labor : Exogenous, calibrated in the baseline AEEI : Exogenous, calibrated in the Baseline No endogenous R & D and technological progress	-no TFP - Energy efficiency measures with cost potential	- via elasticity of demands to sectoral outputs - via endogenous technology adoption -	Under development	- Exogenous Hicks neutral TC for final good - Endogenous investment in Energy R&D calibrated to replicate assumptions on trends (efficiency gains, learning) in the baseline + Induced technical change in mitigation scenarios; - LbR energy efficiency (with international spillover) + cellulosic biofuels
Does the model includes CCS ? in which sectors (energy, transport) ? With which fuels ?	Yes. All sectors, but ceiling is possible.	Not in the standard version, but we have a version of GEMINI-E3 which takes into account a more relevant description of the electricity sector with CCS for coal power plant	detailed CCS for Public Energy Prod., Conversion, Industry / Coal, Gas, Lignite	Yes: electricity, oil extraction, hydrogen production, production of synthetic fuels from coal	CCS for power plants and H2 production	CCS with coal in the electricity sector.
Status of renewables	One aggregate	Not in the standard	Public Energy	Wind, solar	All major	Wind&Solar

?	non-fossil fuel with LbD	version, but we have a version of GEMINI-E3 which takes into account a more relevant description of the electricity sector with renewable (hydro and others)	Prod: all RES, Transport: Biofuels, Residen. Commerc.: Biomass,Solar, Geo	geothermal, tidal, hydro, biomass, biofuels.	renewable sources included in detail	for power generation subject to LbD. Biofuels in non electricity mix subject to Learning by Researching.
Nuclear options: exogenous constraints ? fast breeder ?	No	Not in the standard version, but we have a version of GEMINI-E3 which takes into account a more relevant description of the electricity sector with nuclear power plant (but not with fast breeder)	Nuclear restricted on country level fast Breeder = Yes	Existing nuke, new nuke (fast breeder). Exogenous upeer and lower bounds on nuclear capacity in each region.	A number of nuclear technologies included	No constraint. Waste management costs calibrated on U.S. Yucca mountain repository costs, growing linearly with capacity installed.
EMISSIONS						
Gases included	CO2, remainder exogenous	CO2, CH4, N20, Fluorinated gases	CO_2, CH_4, N_2O, NO_x, SO_2, CO, NMVOC, PM_{10}, $PM_{2.5}$	CO_2, CH4, N2O,	CO2, CH4, N2O	CO_2, CH4, N2O, Fluorinated, SO2
LULUCF	No	No	not LULUCF	Exogenous for now (in the process of updating)		Exogenous (but linkages with Global Timber Model (B. Sohngen))
POLICY INSTRUMENTS						
What are the instruments that can be represented?	Carbon tax, energy tax, fossil fuel tax, CCS tax applicability, non-FF subsidy, renewable portfolio standard, carbon portfolio standard	Tax (national, regional or international), EU ETS, etc	Carbon tax, Renewable quotas, Feed in tariffs, Energy efficiency policies	All instruments, except those related to recycling of revenues from taxes and permits to the economy at large.	Anything that can be represented in a social planner, global optimization framework	Global carbon tax, global and regional carbon markets, technology policies, energy efficiency policies
Tradable Permits : Allocation? Banking & borrowing? ?	NA	Tradable Permits allowed Allocation exogenous Banking borrowing : no	Sector and technology specific permits, no banking, no borrowing	All types are possible.		Exogenous Allocation of permits. Banking and borrowing can be modelled
Costs of policy instruments?	Full costs in terms of EV, or GDP, or NPV consumption loss	GDP, surplus,	Additional system costs of instrument		Divergence from minimum system costs, without policy intervention, can be calculated ex-post.	Full economic costs. Crowd out effects. Free-riding incentives costs.

In addition, partners were asked to indicate the main expected model enhancements. This serves as a sum up of the detailed reporting of each modeling group.

Expected model enhancement

Model Name	DEMETER (UNIMAN)	GEMINI-E3 (ORDECSYS)	PEM / TEAMS (USTUTT)	TIAM (KANLO)	TIAMEC (ECN)	WITCH (FEEM)
	Further work on CCS	Cost of technologies, New technologies developments Possibility to link GEMINI-E3 with the TIAM Model, methodology under development with the KANLO team.	Expansion of technology database, Additional trades for energy carriers	Database improvement Enhanced Stochastic Programming capability	Increasing the flexibility of the model by reducing its extensive technological description of the energy system	Calibrate at 2005. Model all GHGs. More technological detail in the non-electric sector.

3. WITCH (FEEM)

The WITCH model and detailed structure are described in Bosetti et al (2006)[1] and Bosetti, Massetti and Tavoni (2007). The objective of this report is to describe key progress made since the development of WITCH. This include the updating of the base year data base to 2005, and new dynamic calibration of the main driving forces (Section 1); the explicit inclusion of non industrial greenhouse gases and abatement options (Section 2); new specification of low carbon technologies and technological progress (Section 3); computational advancements (Section 4).

1. Database updating and revision

WITCH08 has been updated with more recent data and revised estimates for future projection of the main exogenous drivers. The base calibration year has been set at 2005, for which socio-economic, energy and environmental variables data is now available. We report on the main hypothesis on current and future trends on population, economic activity, energy consumptions and climate variables.

1.1. Population

An important driver for the emissions of greenhouse gases (GHG) is the rate at which population grows. In the WITCH model, population growth is exogenous. We update the model base year to 2005, and use the most recent estimates of population growth. produced by the UN Population Division are used for the first 50 years[2].

1.2. Economic activity

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in 2005 US$[3]. We maintain the use of market exchange rates (MER)[4].

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[1] Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni, (2006). "WITCH: A World Induced Technical Change Hybrid Model." The Energy Journal, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

[2] The data is available from: http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

[3] http://go.worldbank.org/U0FSM7AQ40

[4] This is in line with most of the practice in energy-economic-environment modelling. There has been recent intense debate on the use of MER vs. purchasing power parity (PPP) exchange rate, in particular in relation to the implications for greenhouse gases emission trajectories. MER might underestimate current relative output levels of low-income countries by a factor of around three relative to high-income countries, because tradable goods are currently relatively more expensive in low income countries than in high income countries (the Harrod–Balassa–Samuelson effect). However, output data is more readily available and reliable in MER, and allows for better comparison of both

World GDP in 2005 equals to 44.2 Trillions US$.

1.3. Energy data

The energy sector is composed by the electricity production sector and non-electric sector, which consumes energy of different sources. WITCH08 maintains the same underlying structure as the previous version of the model, but the data is updated using ENERDATA (2008).

1.3.1. Power generation sector

We maintain the same specification as in WITCH05 for the capacity factors, specified by type of power generation plant. We then retrieve the implicit capacities installed, which differ from the real capacities installed because of different factors' employment. Despite the detailed description of the power generation sub-sector, not all types of power plants are modelled explicitly in WITCH (for instance, the model does not distinguish gas with no combined cycle): we therefore assume the standard use of factors for new power plants. This assumption helps us to avoid accounting difficulties for multi-fuel and marginal power plants. We maintain the same specification as in WITCH05 for the efficiency of fuel consumption in power generation plants, since they are close to the implied values in the new Enerdata database. The specification of renewable energy sources is an important aspect of climate-economy models. Following recent debates over the technical readability, we increase the investment costs for Integrated Gasification Combined Cycle (IGCC) technologies from 2000 1995USD/kW to 2500 1995USD/kW. A similar increase is applied to nuclear power generation.

We assume the average efficiency of gas and coal power plants improves autonomously to 60% and 45% respectively over the next decades. Similarly, the utilization factor of Wind&Solar is assumed to increase from 2500 to 3500 hours per year.

1.3.2. Non electricity sector

For the non-electric sector, we derive the updated figures from the Enerdata 2008 database, by subtracting energy consumptions in the electricity sector from total consumption figures. It is to be noted that the electricity consumption figures reported in the Enerdata 2008 are slightly different from electricity consumption in WITCH08, because of different assumptions about the efficiency of electricity production. The discrepancy is however negligible.

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output growth and carbon intensities with historical empirical studies, that mostly rely on the MER metric, as well as short term projections of economic and energy variables. Furthermore, the lower carbon efficiency of developing countries implicit in MER calculations with respect to PPP do not necessarily translate in higher emission projections, given that income elasticity of energy demand is higher under the latter, so that lower autonomous efficiency improvements should be assumed for PPP projection. The eventual effect on emissions is unclear, and might be not too significant.

1.3.3. Prices of fossil fuels and exhaustible resources

The prices of fossil fuels and exhaustible resources have been revised upwards, following the sharp increases in the market prices between 2002 and 2005. Price growth prospects have remained however similar: we thus kept a similar evolution as in WITCH05, adjusting it to the new starting value for 2005. Price ratios are taken from Enerdata, IEA WEO2007 and EIA AEO2008. The 2005 prices for exhaustible resources are set at:

- 55$/bbl for oil, or roughly 8$/GJ. In this updated version, we modify price mark-up values in order to keep the price of producing countries at half the level of importing countries, as in WITCH05. We simplify the assumptions for the use of fossil fuels in the non-electricity sector, using the same values as for electricity.
- 5.5 $/GJ for natural gas.
- 60$/ton for coal, equivalent to 2$/GJ. In order to match the large difference in price increases shown in the Enerdata database, we adjust the mark-up prices.
- Uranium ore price tripled from 2002 to 2005[5], and we thus update to this new level. The cost of conversion was increased from 5$/kg to 11$/kg[6], while enrichment costs stayed roughly constant[7]. We thus slightly increased the cost of conversion and enrichment from 221 to 230 1995 $/kg.

1.3.4. Carbon emission coefficients of fossil fuels

In WITCH08 we maintain the same initial stoichiometric coefficients as in WITCH05. However, in order to differentiate the higher emission content of non-conventional oil as opposed to conventional ones, we link the carbon emission coefficient for oil to its availability. Specifically, the stoichiometric coefficient for oil increases with the cumulative oil consumed so that it increases by 25% when 2000 Billions Barrels are reached. An upper bound of 50% is assumed. The 2000 figure is calibrated on IEA 2005[8] estimates on conventional oil resource availability. The 25% increase is chosen given that estimates[9] range between 14% and 39%.

1.4. Climate data and feedback

We continue to use the MAGICC 3-box layer climate model. CO2 concentrations in the atmosphere have been updated to 2005 at roughly 385ppm and temperature increase above pre-industrial at 0.76°C, in accordance with IPCC 4ar (2007). Other parameters governing the climate equations have been adjusted following Nordhaus (2007)[10]. We have replaced the exogenous non-CO2 radiative forcing with specific representation of other GHGs and sulphates, see Section 2.

The damage function of climate change on the economic activity is left unchanged.

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[5] http://www.uxc.com/review/uxc_g_price.html
[6] http://www.uxc.com/review/uxc_g_ind-c.html
[7] http://www.uxc.com/review/uxc_g_ind-s.html
[8] IEA 2005, Resources to Reserves – Oil & Gas Technologies for the Energy Markets of the Future
[9] Farrell and Brandt, 2005
[10] http://nordhaus.econ.yale.edu/DICE2007.htm

2. Additional sources of GHGs

2.1. Non-CO2 GHGs

Non-CO2 GHGs are important contributors to global warming, and might offer economically attractive ways of mitigating it[11]. WITCH05 only considers explicitly industrial CO2 emissions, while other GHGs, together with aerosols, enter the model in an exogenous and aggregated manner, as a single radiative forcing component.

In WITCH08, we take a step forward and specify non-CO_2, modelling explicitly emissions of CH_4, N_2O, SLF (short lived fluorinated gases, i.e. HFCs with lifetimes under 100 years) and LLF (long lived fluorinated, i.e. HFC with long lifetime, PFCs, and SF6), in addition to industrial CO_2. We also distinguish SO_2 aerosols, which have a cooling effect on temperature.

Since most of these gases are determined by agricultural practices, we rely on estimates for reference emissions and a top-down approach for mitigation supply curves. For the baseline projections of non-CO2 GHGs, we use EPA regional estimates[12]. The regional estimates and projections are available to 2020 only: beyond that date, we use growth rates for each gas as specified in the IIASA-MESSAGE-B2 scenario[13], that has underlying assumptions similar to the WITCH ones. SO2 emissions are taken from MERGE v.5[14] and MESSAGE B2: given the very big uncertainties associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measure will converge to the similar values.

The equations translating nonCO_2 emissions into radiative forcing are taken from MERGE v.5. The global warming potential (GWP) methodology is employed, and figures for GWP as well as base year stock of the various GHGs are taken from IPCC Fourth Assessment Report, Working Group I. The simplified equation translating CO2 concentrations into radiative forcing has been modified from WITCH05 and is now in line with IPCC[15].

We introduce end-of-pipe type of abatement possibilities via marginal abatement curves (MACs) for nonCO2 GHG mitigation. We use MAC provided by EPA for the EMF 21 project[16], aggregated for the WITCH regions. MAC are available for 11 cost categories ranging from 10 to 200 $/tC. We have ruled out zero or negative cost abatement options. MAC are static projections for 2010 and 2020, and for many regions they show very low upper values, such that even at maximum abatement, emissions would keep

[11] See the Energy Journal Special Issue (2006) (EMF-21), and the IPCC 4ar WG III
[12] EPA Report 430-R-06-003, June 2006. the report is available from:
http://www.epa.gov/climatechange/economics/mitigation.html.
[13] Available at
http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=regions
[14] http://www.stanford.edu/group/MERGE/m5ccsp.html
[15] http://www.grida.no/climate/ipcc_tar/wg1/222.htm, Table 6.2, first Row
[16] http://www.stanford.edu/group/EMF/projects/projectemf21.htm

growing over time. We thus introduce exogenous technological improvements: for the highest cost category only (the 200 $/tC) we assume a technical progress factor that reaches 2 in 2050 and the upper bound of 3 in 2075. We however set an upper bound to the amount of emissions which can be abated, assuming that no more than 90% of each gas emissions can be mitigated. Such a framework enables us to keep nonCO2 GHG emissions somewhat stable in a stringent mitigation scenario (530e) in the first half of the century, and subsequently decline gradually. This path is similar to what is found in the CCSP report[17], as well as in MESSAGE stabilisation scenarios. Nonetheless, the very little evidence on technology improvements potential in nonCO2 GHG sectors indicates that sensitivity analysis should be performed to verify the impact on policy costs.

2.2. Forestry

Forestry is an important contributor of CO2 emissions and, similarly to nonCO2 gases, it is believed it could provide relatively convenient abatement opportunities. Forestry sector models differ substantially from energy-economy ones, so that normally the interaction is solved via soft link (eg iterative) coupling. For example, WITCH05 has been coupled with a global timber model to assess the potential of carbon sinks in a climate stabilization policy[18]. However, the model didn't include this option in the standard simulation exercises.

WITCH08 is enhanced with baseline emissions and supply mitigation curves for reduced deforestation. The focus is given to REDD given its predominant role to CO2 emissions and the policy importance of this option as stressed by the 2007 Bali Action Plan.

Baseline emissions are provided by Brent Sohngen GTM model. REDD supply mitigation cost curves have been built and made them suitable to be incorporated in the WITCH model. Curves are from Woods Hole[19] and focus on Brasil and Congo. Supply estimates from the tropical asia region will be also included once available.

3. Abatement Technologies

3.1. Innovative carbon free technologies

In the short to mid term, energy savings, fuel switching in the power sector mainly, as well as non fossil fuel mitigation are believed to be the most convenient mitigation options. In the longer term, however, one could envisage the possibility that innovative technologies, currently far from being commercial, are developed, with low or zero carbon emissions. These technologies are usually referred to in the literature as backstop technologies, and are characterized as being available in large supplies. A Backstop technology can be better thought of as a compact representation of a portfolio of advanced technologies, that would ease the mitigation burden away from currently commercial options, though it would become available not before a few decades. This

[17] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm
[18] Tavoni et al. (2007)
[19] http://whrc.org/BaliReports/

representation has the advantage of maintaining simplicity in the model by limiting the array of future energy technologies and thus the dimensionality of techno-economic parameters for which reliable estimates and meaningful modelling characterization exist.

WITCH05 features a series of mitigation options in both the electric and non-electric sectors, such as nuclear power, CCS, renewables, biofuels etc. However, limited deployment potential of controversial technologies such as nuclear and resource constrained ones such as bioenergy suggests that the possibility to invest towards the commercialization of innovative technologies should be a desirable feature of models that evaluate long-term policies.

To this extent, WITCH08 is enhanced by the inclusion of two new backstop technologies that necessitate dedicated innovation investments to become economically competitive even assuming a climate policy. We follow the most recent characterization in the technology and climate change and technology policies, modelling the costs of the backstop technologies with a two-factor learning curve in which the price of the technologies declines both with investments in dedicated R&D and with technology diffusion. This improved formulation is meant to overcome the main criticism of the single factor experience curves[20] by providing a more structural -R&D investment led-approach to the penetration of new technologies, and thus to ultimately better inform policy makers on the innovation needs in the energy sector. Modelling of long term and uncertain phenomena such as technological evolution calls for caution in the interpretation of exact quantitative figures, and to accurate sensitivity analysis. The model parsimony allows for tractable sensitivity studies, as stressed above. One should nonetheless keep in mind that economic implication of climate policies as well as carbon price signals are influenced by innovative technologies availability only after 2030.

More specifically, we model the investment cost in a technology *tec* as being influenced by a learning by researching process (main driving force before adoption) and by learning by doing (main driving force after adoption), the so called 2 factor learning curve formulation[21]. $P_{tec,t}$, the unit cost of technology tec at time t is a function of deployment, $CC_{tec,t}$ and dedicated R&D stock, $R\&D_{tec,t}$ as described in equation [1]:

$$\frac{P_{tec,T}}{P_{tec,0}} = \left(\frac{R\&D_{tec,T-2}}{R\&D_{tec,0}}\right)^{-c} * \left(\frac{CC_{tec,T}}{CC_{tec,0}}\right)^{-b}$$

where the *R&D stock* accumulates with the perpetual rule

$$R\&D_{tec,T+1} = R\&D_{tec,T} \cdot (1-\delta) + IR\&D_{tec,T}$$

and *CC* is the cumulative installed capacity (or consumption) of the technology. **[1]**

[20] Nemet, 2006
[21] Kouvaritakis et al., 2000

We assume a two-period time (eg 10 yrs) interval between R&D knowledge and its effect on the price of the backstop technologies to account for time lags between research and commercialization.

The two exponents are the learning by doing index $(-b)$ and the learning by researching index $(-c)$. They define the speed of learning and are derived from the learning ratios. The learning ratio lr is the rate at which the generating cost declines each time the cumulative capacity doubles, while lrs is the rate at which the cost declines each time the knowledge stock doubles. The relation between b, c, lr, and lrs can be expressed as follows:

1 – lr= 2^-b and 1 – lrs= 2^-c

We set the initial prices of the backstop technologies at roughly 10 times the 2005 price of commercial equivalents (10,000 US$/kW for electric, and 500$/bbl for non electric). The cumulative deployment of the technology is initiated at 1000twh and EJ respectively, an arbitrarily low value[22]. The backstop technologies is assumed to be renewable in the sense that the fuel cost component is negligible; for power generation, it is assumed to operate at load factors comparable with those of baseload power generation.

This formulation has been received significant attention from the empirical and modelling literature in the most recent past[23]. Estimates of parameters controlling the learning processes vary significantly across studies, see Table 1. They also primarily focus on power generation. For WITCH08 we take averages of the values in the literature, as reported in the last row of the table. Note that the value chosen for Learning by doing parameter is lower than those normally estimated in single factor experience curves, since part of the technology advancement is now led by specific investments. This more conservative approach reduces the role of black box autonomous learning, which has been criticized for being too optimistic and leading to excessively low costs of transition towards low carbon economies.

Table 1: Learning ratios for diffusion (Lbd) and innovation (LbS) process.

Technology	Author	Lbd	LbS
Wind	Criqui et al 2000	16%	7%
	Jamasab 2007	13%	26%
	Soderholm and Klassens 2007	3.1%	13.2%
	Klassens et al 2005		12.6%
PV	Criqui et al 2000	20%	10%
Solar Thermal	Jamasab 2007	2.2%	5.3%
Nuclear Power (LWR)	Jamasab 2007	37%	24%

[22] Kypreos, 2007
[23] Criqui et al 2000, Barreto and Kypreos, 2004, Klassens et al 2005, Kypreos 2007, Jamasab, 2007, Soderholm and Klassens 2007

CCGT (1980-89)	Jamasab 2007	0.7%	18%
CCGT (1990-98)	Jamasab 2007	2.2%	2.4%
WITCH08		*10%*	*13%*

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. We assume that once the backstop technologies become competitive thanks to dedicated R&D investment and pilot deployments, their uptake will not be immediate and complete, but rather there will be a transition/adjustment period. These penetration limits are a reflection of inertia in the system, as presumably the large deployment of backstops will require investment in infrastructures and the re-organization of the economic system. The upper limit on penetration is set equivalent to 5% of the total consumption in the previous period by technologies other than the backstop, plus the electricity produced by the backstop.

3.2. International spillovers of knowledge and experience

Learning process via knowledge investments and experience are likely not to remain within the boundaries of single countries, but to spill to other regions too. The effect of international spillovers is deemed to be very important, and its inclusion in integrated assessment models desirable, since it would allow for a better representation of the innovation market failures and for specific policy exercises. The WITCH model is particularly suited to perform this type of the analysis, since its game theoretic structure allows to distinguish first and second best strategies, and to thus quantify optimal portfolio of policies to resolve all the externalities arising in global problems such as climate change.

WITCH05 featured spillover of experience for Wind&Solar in that the Learning by Doing effect depended on world cumulative installed capacity, so that single regions could benefit from investments in virtuous countries, thus leading to strategic incentives. An enhanced version was developed to include spillovers in knowledge for energy efficiency improvements[24].

In WITCH08 we continue along this strand of research and model spillover of both experience and knowledge in the newly featured backstops technologies. Similarly to the learning by doing for Wind&Solar, we assume experience accrues with the diffusion of technologies at the global level. We also assume knowledge spills internationally. The amount of spillovers entering each world region depends on a pool of freely available knowledge and on the ability of each country to benefit from it, i.e. on its absorption capacity. Knowledge acquired from abroad combines with domestic knowledge stock and investments and thus contributes to the production of new technologies at home. The parametrization follows Bosetti et al 2008.

[24] Bosetti et al, 2008

4. Computational issues

The WITCH model is solved numerically using GAMS – General Algebraic Modelling System[25]. GAMS is a high-level modelling system for mathematical programming problems, designed to provide a convenient tool to represent large and complex model in algebraic form, allowing a simple updating of the model and flexibility in representation, and modular construction.

WITCH features 2 different solution concepts, a cooperative that optimizes jointly all regions, and a non-cooperative decentralized one that is achieved iteratively via an open loop nash algorithm in which each region is optimized separately. This second solution was carried out in WITCH05 sequentially.

In WITCH08, the regional maximisation problems for the non-cooperative solution are solved in parallel as opposed to sequentially, exploiting new computing power afforded by multiple-core hardware, and thus allowing for a much more rapid solution of the overall optimisation exercise. The solutions of each region's maximisation problem are combined in a single step following each iteration – the total number of parallel solves is therefore equal to the number of regions – twelve in the case of WITCH. The speed of the solution is thus determined by the slowest region.

The model also runs in batch mode for remote solution, using SSH interface and a system of shared files, stored in the remote host computer. The use of Globus Toolkit 4 allows the submission of the solve jobs to more than one cluster, thus further reducing the execution time needed to find a solution.

Several tests have been performed for evaluating the scalability and performance of the parallel algorithm (Figure 1). The execution tests have been made on the SPACI's HP-XC6000 cluster ranging from 1 up to 12 CPUs. Since the GAMS executable is not available for the considered architecture, an emulator for x86_32 processors has been used. The analytic model of the parallel execution time highlights how the coarse grained parallelization produces a decreasing efficiency starting from 6 processors. The motivation resides on the not well balancing of the workload.

[25] http://www.gams.com/

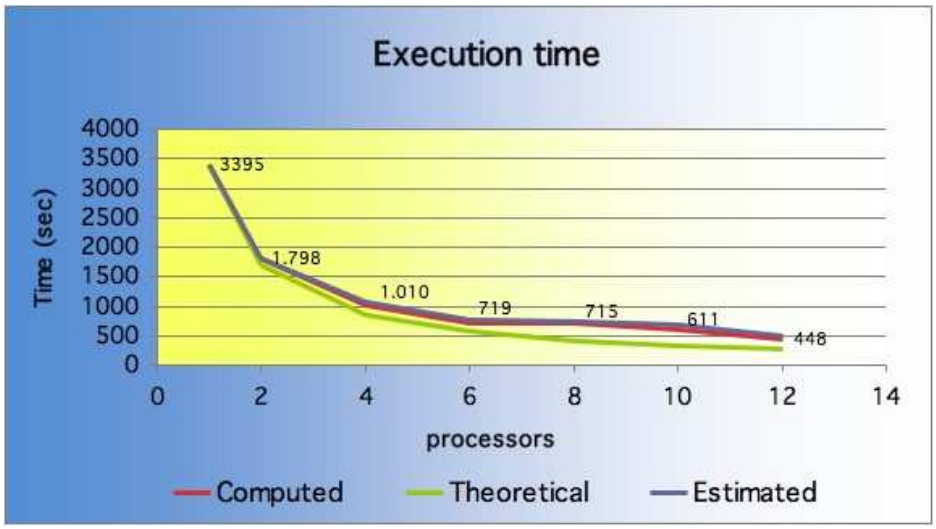

Figure 1

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4. TIAMEC (ECN)

Introduction and background

In addition to having a long experience in using MARKAL models (see e.g. [1, 2] for some recent studies), ECN has recently also expanded its modeling portfolio to include TIMES [3], a modeling framework based on the integration of MARKAL and EFOM approaches. However, spatially the modeling focus of ECN has previously mostly been on the development of the European and Dutch energy systems and the rest of the world has been excluded from the explicitly modeled system. In order to be able to describe issues related to, for example, trade flows, resource extraction and climate change, modeling Europe, or the Netherlands, alone no longer provides a suitable spatial framework for dealing with these questions. Therefore a decision was made to acquire TIAM, **T**IMES **I**ntegrated **A**ssessment **M**odel, a global long term model, covering the extraction and conversion of energy across the 15 defined world regions until 2100. This model includes a number of characteristics that make it especially suitable for the PLANETS project. The model was received in March 2008, after which the study and the development of the model could begin.

TIAM

TIAM [4] is a bottom-up, technology rich linear optimization model, describing the development of the global energy system over a long period of time, usually some 100 years. The regional disaggregation most common for TIAM, and also used in our version, separates the world into 15 different world regions[26].

The model explicitly describes many interactions and dynamics, previously unavailable in the regional models used at ECN. For example, resource extraction and global trade

[26] Versions with 16 regions, the additional region being a country extracted from one of the 15 regions and for which the results are of increased importance, are also under development by some institutes [5].

can be included endogenously, while previously separate assumptions had to be made on the available trade flows as well as the costs of the traded fuels.

TIAM also includes an option to use a built-in climate module, therefore also allowing the model to be constrained based on climate implications, instead of the usual proxy, emissions.

The technology database of the TIAM model is extensive, covering the full range of the energy chain, from resource extraction to the final end-use consumption. The exogenously defined demands for energy services can also be modeled with price elasticities, so that they are sensitive to price changes. Figure 1 shows a simplified sketch of the modeled reference energy system. In addition to the energy flows and conversion stages shown, also environmental variables are represented. In order to provide complete emission inputs for the climate module, emissions originating outside the energy sector are also included.

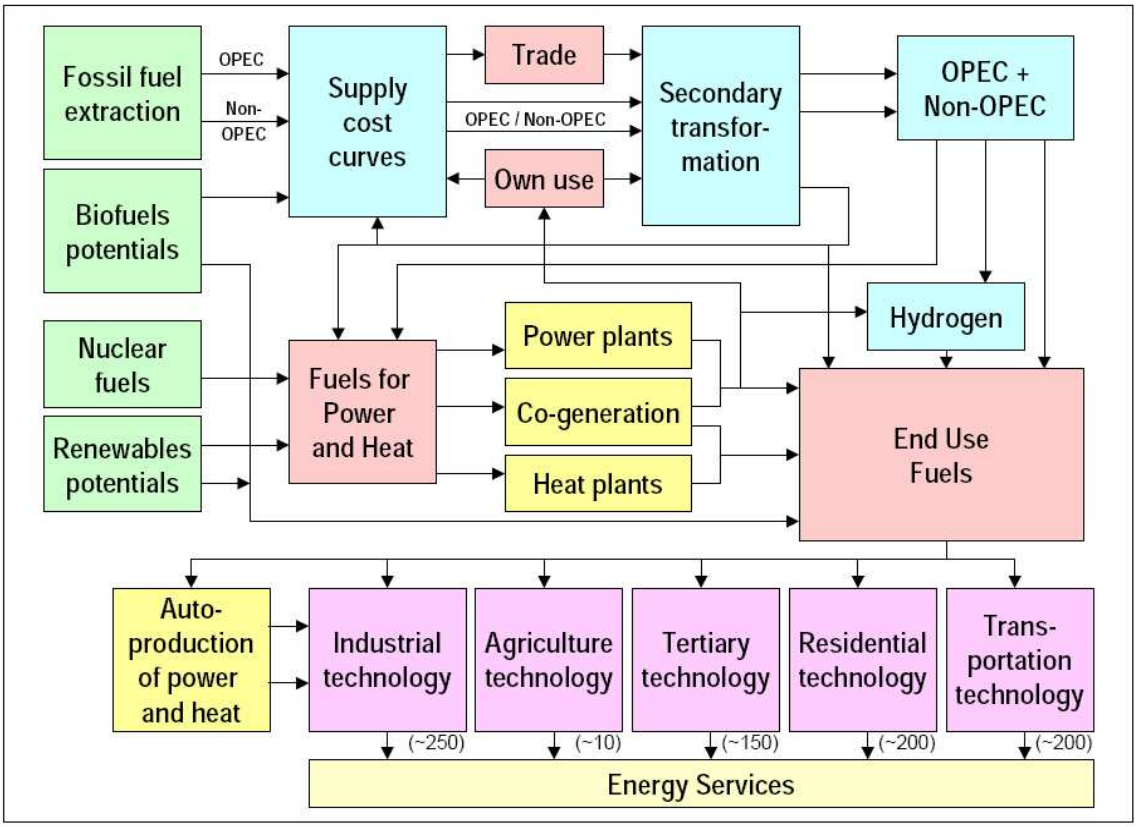

Figure 1. Structure of the reference energy system [5].

Developing TIAMEC

The development of the ECN version on TIAM has, and will, concentrate mainly on increasing the flexibility of the model by reducing its extensive technological description of the energy system, while hopefully simultaneously keeping the more general, aggregated view unchanged. In this sense, the goal is to trade the ability to say things about even very detailed changes in the energy system to a slimmer and more easily adoptable model. After new newly acquired model was carefully studied in details, this downsizing development has recently begun and will be ongoing throughout the PLANETS project. A main sector of focus is the demand side, for which more aggregate description is planned and more extensive modeling of stylized energy conservation measures, instead of specific technologies, is foreseen. Careful consideration will, however, be paid to make sure that further changes in the model do not affect results and drawn conclusion too drastically.

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5. TIAM (KANLO)

TABLE OF CONTENTS

1 Introduction 24

2 Inputs and Outputs of TIMES 25

2.1 The TIMES Input Scenario 25
2.1.1 The Demand Component of a TIMES scenario 25
2.1.2 The Supply Component of a TIMES Scenario 26
2.1.3 The Policy Component of a TIMES Scenario 26
2.1.4 The techno-economic component of a TIMES scenario 27
2.2 TIMES outputs 27

3 The structure of a TIMES model 28

3.1 Structure vs. data 28
3.2 Time in TIMES 28
3.3 The RES concept 28
3.4 Overview of the TIMES attributes 33
3.4.1 Parameters associated with processes 33
3.4.2 Parameters associated with commodities 33
3.4.3 Parameters attached to commodity flows into and out of processes 33
3.4.4 Parameters attached to the entire RES 33
3.5 Managing and running a TIMES model (major enhancement) 33

4 Economic rationale of TIMES 34

4.1 The TIMES paradigm 34
4.1.1 Multi-regional feature 34
4.1.2 Partial equilibrium properties 35
4.1.2.1 Linearity 35
4.1.2.2 Maximization of total surplus: Price equals Marginal value 35
4.1.2.3 Competitive energy markets with perfect foresight 37
4.1.2.4 Marginal value pricing 38

5 Three optional features of TIMES 38

5.1 The Lumpy Investment option 38
5.2 Endogenous Technological Learning (ETL) 38
5.3 Stochastic Programming 39

6 The Climate Module of TIAM (major enhancement) 40

6.1 Concentrations (accumulation of CO2, CH4, N2O) 41
6.1.1 CO2 concentration 41
6.1.2 CH4 concentration 41
6.1.3 N2O concentration 42
6.2 Radiative forcings 42
6.2.1 Forcing from CO2 42
6.2.2 Forcing from CH4 43

6.2.3 Forcing from N2O 43
6.3 Temperature increase 44
7 TIAM Data Base Improvements (major enhancements) 44
7.1 Emission trading mechanisms 45
7.2 Electric Power Generation sector (EPG) 45
7.3 Alternate energy production 50
7.4 Technologies with CO2 capture and storage (CCS) 50
7.5 Transportation sector 50
8 References 53

Introduction

In this report, the principal characteristics of the TIMES model and of its global incarnation as ETSAP-TIAM are presented and discussed, including the recent enhancements and additions relevant for the PLANETS project.

TIMES was conceived as a descendent of the MARKAL and EFOM paradigms, to which several new features were added to extend its functionalities and its applicability to the exploration of energy systems and the analysis of energy and environmental policies. This report summarizes the main features and additions to the TIAM model, while a series of two articles (Loulou, 2007, Labriet and Loulou, 2007) are devoted to the more detailed formulation of TIMES paradigm and equations and of the TIAM instance of TIMES. An even more complete technical description of TIMES appears in the full documentation available on the ETSAP web site at www.etsap/org/documentation

The Energy Technology Systems Analysis Programme (ETSAP) is at the source of the development of TIMES and of its TIAM instance.
The ETSAP TIMES model (an acronym for The Integrated MARKAL-EFOM System), was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement under the aegis of the International Energy Agency (IEA). The TIMES Integrated Assessment Model (ETSAP-TIAM) is the global multiregional incarnation of the TIMES model generator.

TIMES is a model generator for local, national or multi-regional energy systems, which provides a technology rich basis for estimating energy dynamics over a long-term, multiple period time horizon. It is usually applied to the analysis of the entire energy sector, but may also applied to study in detail single sectors (e.g. the electricity and district heat sector).

In TIMES, reference case projections of end-use energy service demands (e.g., car road travel, residential lighting, steel production and the like) 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 in the base year, 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 model aims to supply energy services at minimum global cost (more accurately at minimum loss of total surplus) by simultaneously making decisions on equipment investment, equipment operation, primary energy supply, and energy trade. TIMES is thus a vertically integrated model of the entire extended energy system.

The scope of the model extends beyond purely energy related issues, to the representation of environmental emissions, and perhaps materials, related to the energy system. The model is well suited to the analysis of energy-environmental policies, which may be represented with accuracy thanks to the explicitness of the representation of technologies and fuels in all sectors.

In TIMES, the quantities and prices of the various commodities are in equilibrium, i.e. their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. This equilibrium has the property that the total surplus (consumers plus producers surpluses) is maximized.

In addition, TIMES includes a climate module that calculates the impact of energy decisions on greenhouse gas emissions and concentration, as well as on the

resulting changes in atmospheric forcing, and in global temperature. The Climate Module is especially useful in global incarnations of TIMES, such as TIAM.

TIMES was developed as a successor of the MARKAL (Fishbone et al., 1981, 1983, Berger et al., 1992), and EFOM (Finon, 1974, Van Voort, 1984) bottom-up energy models, and incorporates the features of these ancestors, plus several new features. From MARKAL, TIMES inherits the detailed description of technologies, the RES concept, and the equilibrium properties. From EFOM, TIMES inherits the detailed representation of energy flows at the technology level. In addition, TIMES has specific features that were not present in the ancestor models (at least in their earlier incarnations), as follows:

- Variable length periods;
- Vintaged technologies;
- Detailed representation of cash flows in the objective function;
- Technologies with flexible inputs and flexible outputs;
- Stochastic programming with risk aversion ;
- Climate module ;
- Endogenous energy trade between regions.

Section 2 describes the inputs and outputs of TIMES. Section 3 provides a general overview of the representation in TIMES of the Reference Energy System (RES) of a typical region or country, focusing on its basic elements, technologies and commodities. Section 4 discusses the economic rationale of the model, and Section 5 describes three model options: Lumpy Investments (LI), Endogenous Technological Learning (ETL), and Stochastic Programming (SP). Section 6 focuses on the climate module of TIMES. Section 7 indicates the database improvements that were made to TIAM.

In each section of subsection, the recent model enhancements are indicated in the section's title.

Inputs and Outputs of TIMES

The TIMES Input Scenario

The TIMES model is particularly suited to the *exploration* of possible long term energy futures based on contrasted *scenarios*. Given the long horizons simulated with TIMES (up to 2100 in the current versions of the model), the scenario approach is really the only choice. Scenarios, unlike forecasts, do not pre-suppose advance 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 input: 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.

The Demand Component of a TIMES scenario

In TIMES, the set of demand trajectories is obtained by first specifying the values of several *demand drivers* (population, GDP, sector outputs, etc.), which are obtained externally, via other models (such as GEMINI-E3) or from accepted external sources. The divers consist of: GDP, sector outputs, and population in the various regions. Note that GEMINI-E3 itself uses other drivers as inputs in order to derive its own results, e.g. assumptions on technical progress, population, and trade regime. For population and household projections, typical sources include IPCC, Nakicenovic (2000), Moomaw and Moreira (2001). Other approaches may be used to derive TIMES drivers, whether via models or other means. The versions of TIAM operated from 2004 to 2006 used GEM-E3 instead of GEMINI-E3 to derive its demand drivers.

Once the drivers for TIMES are determined and quantified, the construction of the reference demand scenario requires computing a set of *energy service demands* over the horizon. This is done by choosing *elasticities of demands to their respective driver*s, in each region, using the following general formula:

$$Demand = Driver^{Elasticity}$$

The elasticities of demands to their respective drivers reflect the degree of decoupling between the drivers and the demands.

The demands are provided by the user only for the reference scenario. When the model is run for alternate scenarios (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 scenario. 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. In fact, TIMES is driven not by demands but by *demand curves*.

The Supply Component of a TIMES Scenario

The second constituent of a scenario is a set of *supply curves* for primary energy and material resources. Multi-stepped supply curves can be easily modeled in TIMES, each step representing a certain potential of the resource available at a particular cost. In some cases, the potential may be expressed as a cumulative potential over the model horizon (e.g. reserves of gas, crude oil, etc), as a potential over the resource base (e.g. available areas for wind converters differentiated by velocities, available farmland for biocrops, roof areas for photovoltaic installations) and/or as an annual potential (e.g. maximum extraction rates, or annual available wind, biomass, or hydro potentials). Note that the supply component also includes the identification of trading possibilities.

The Policy Component of a TIMES 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 policy targets (such as

general carbon tax, or permit trading system on air contaminants). A simpler example might be a nuclear policy that limits the future expansion of nuclear plants. Another example might be the imposition of fuel taxes, or of industrial subsidies, etc.

The techno-economic component of a TIMES scenario

The fourth and last constituent of a scenario is the set of technical and economic parameters assumed for the transformation of primary resources into energy services. In TIMES, these techno-economic parameters are described in the form of technologies (or processes) that transform some commodities into others (fuels, materials, energy services, emissions). Some technologies may be forced and others may simply be available for the model to choose. The usefulness of a TIMES instance 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 the class of Bottom-up models, to which TIMES belongs[27]. Other classes of 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.

TIMES outputs

For each scenario, TIMES produces two types of result. First, the primal solution of the Linear Program provides, at each time period and in each region:

- A set of investments in all technologies;
- The operating levels of all technologies;
- The imports and exports of each type of tradeable energy forms and materials;
- The extraction levels of each primary energy form and material;
- The flows of each commodity into and out of each technology;
- The emissions of each substance by each technology, sector, and total;
- The changes in concentration of the greenhouse gases ;
- The radiative forcing induced by the atmospheric concentration of GHG in the atmosphere;
- The change in global temperature induced by the change in radiative forcing.

In addition, the dual solution of the Linear Program provides:

- The shadow price of each commodity present in the RES (energy form, demand, emission, material);
- The reduced cost of each technology in the RES, i.e. the required cost reduction to make that technology competitive.

[27] Although TIMES does not encompass the macroeconomic variables beyond the energy sector, accounting for price elasticity of demands captures a major element of feedback effects between the energy system and the economy.

The structure of a TIMES model

Operationally, a TIMES run configures the *energy system* (of a *set of regions*) over a certain *time horizon* in such a way as to *minimize the net total cost* (or equivalently *maximize the net total surplus*) of the system, while satisfying a number of *constraints*.

Structure vs. data

The structure of TIMES is ultimately defined by variables and equations determined from the data input provided by the user. The database itself contains both qualitative and quantitative data. The *qualitative data* includes, for example, lists of energy carriers, the technologies that the modeler feels are applicable (to each region) over a specified time horizon, as well as the environmental emissions that are to be tracked. This information may be further classified into subgroups, for example energy carriers may be split by type (e.g., fossil, nuclear, renewable, etc). The *quantitative data*, in contrast, contains the technological and economic parameter values specific to each technology, region, and time period. When constructing multi-region models it is often the case that a technology may be available for use in two distinct regions; however, cost and performance assumptions may be different. This section discusses both qualitative and quantitative assumptions in the TIMES modeling system.

Time in TIMES

The time horizon is divided into a user-chosen number of time-periods, each model period containing an arbitrary, possibly different number of years. For TIMES all years in a given period are considered identical. In the TIAM case, a long horizon of 100 years is usually selected in order to properly reflect the long term nature of the climate phenomena.

The initial period is usually considered a past period, over which the model has no freedom, and for which the quantities of interest are all fixed by the user at their historical values. The initial period consists in most applications of a single year, in order to facilitate calibration to standard energy statistics. Calibration to the initial period is one of the important tasks required when setting up a new TIMES model.

In addition to time-periods, there are time divisions within a year, also called *time-slices*, which may be defined at will by the user. For instance, the user may want to define seasons, day/night, and/or weekdays/weekends. Time-slices are especially important whenever the mode and cost of production of an energy carrier at different times of the year are significantly different. This is the case for electricity and other non storable energy forms such as low temperature heat.

The RES concept

The TIMES energy economy consists of three types of entity:

- *Technologies* (also called *processes*) are representations of physical devices that transform commodities into other commodities.
- *Commodities* consist of energy carriers, energy services, materials, monetary flows, and emissions, and

- *Commodity flows* are the links between processes and commodities. A commodity flow is of the same nature as a commodity but is attached to a particular process, and represents one input or one output of that process.

It is helpful to picture the relationships among these various entities using a network diagram, referred to as a Reference Energy System (RES). Figure 1 sketches the RES of the TIAM model, applicable to each of the 15 TIAM regions[28]. The main elements of TIAM's RES are now briefly described:

- *Energy supply sector:* Each primary energy form is extracted from multiple layers of reserves (fossil, biomass) or of resource potentials (non-fossil energy such as wind, hydro, shallow, deep and very deep geothermal, etc.) , each with a potential and a specific unit cost. This constitutes a supply curve for each energy form. The primary energy resources and forms modeled in TIAM are: coal (4 resources, 2 forms), crude oil (21 resources, 4 forms), natural gas (11 resources, 1 form), and solid biomass (8 resources, 6 forms).
- *Trade:* The following types of energy are endogenously traded between the 15 TIAM regions: coal (brown and hard coals), crude oil, refined petroleum products (gasoline, diesel, heavy fuel oil and naphta), natural gas, liquefied natural gas, natural gas liquids, and atmospheric emissions. The prices of these energy forms are therefore endogenously computed by the model; the impact of environmental policies on energy and permit trade is thus taken into account.
- *Energy transformation:* crude oil is transformed into 15 RPP's via refinery processes; solid biomass may be transformed into alcohols; coal and natural gas may be transformed into hydrogen via gasification or reforming (hydrogen might also be produced by electrolysis); natural gas is liquefied and LNG is gasified and via appropriate processes.
- *Energy conversion:* Electricity is produced by a large number of technologies, each of which takes as input one or more primary resources, such as coal, gas, heavy oil, wind, hydro, etc..
- *Energy consumption sectors:* End-use sectors include Residential, Commercial, Industry and Transportation. Each has several independent demands for energy services, shown in table 1. Each energy service may be satisfied by an array of end-use technologies in competition.
- *Emissions and emission reduction options:* TIAM models emissions of the following greenhouse gases (GHG): CO_2 from energy consumption, , CH_4 from energy consumption (including leakages) as well as from some non-energy sectors (landfills, manure, wastewater, non-energy biomass burning, enteric fermentation and rice cultivation) and N_2O from energy consumption as well as from adipic and nitric acid industries. All GHGs emissions are also merged into a single CO_2-equivalent emission, based on their global warming potential, and used as input into the climate module (see section 6) . Emission mitigation may be accomplished in a number of ways, via energy substitutions; improved efficiency of installed devices; specific non-CO_2 abatement devices (e.g. CH_4 flaring or utilization for electricity production , suppression of leakages at

[28] Africa, Australia-New-Zealand, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Mexico, Middle-East, Other Developing Asia, So-Korea, USA, Western Europe.

natural gas transmission level, N_2O thermal destruction, anaerobic digestion of wastes with gas recovery, etc.); sequestration (CO_2 capture and underground storage, biological carbon sequestration,); and demand reductions (in reaction to increased carbon prices).

Note also although agricultural GHG emissions are accounted for, some of them have no abatement options (i.e. CH_4 emissions from wastewater, biomass burning, enteric fermentation, and rice paddies). Endogenous trade of all emissions is available, so that permit trade can be easily represented within the model.

- Due to its detailed technological nature, TIAM is able to simulate almost any type of emission abatement measure, be it a regulation, a tax, a cap-and-trade system, a portfolio standard, etc.
- Finally, the initial year of the database is calibrated to the energy balances provided by the International Energy Agency, and the characteristics of the technologies and reserves are based on literature or expert knowledge (IPCC reports, US-Environmental Protection Agency, IEA-Energy Technology Perspectives, US-Department of Energy, US Geological Survey, World Energy Council, etc.).

Figure 1. Sketch of the TIAM model's RES

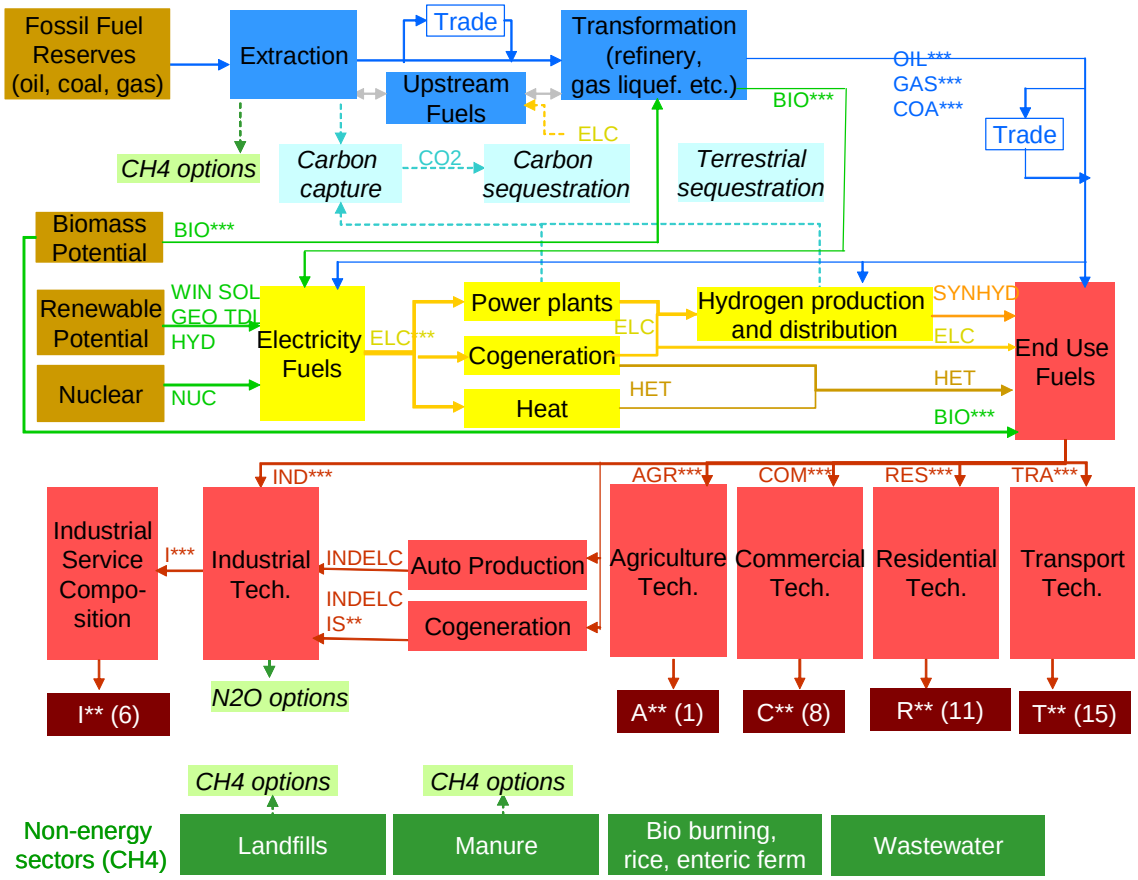

Table 1: End-use demands in TIAM

	Code	Unit
Transportation segments (15)		
Autos	TRT	Billion vehicle-km/year
Buses	TRB	Billion vehicle-km/year
Light trucks	TRL	Billion vehicle-km/year
Commercial trucks	TRC	Billion vehicle-km/year
Medium trucks	TRM	Billion vehicle-km/year
Heavy trucks	TRH	Billion vehicle-km/year
Two wheelers	TRW	Billion vehicle-km/year
Three wheelers	TRE	Billion vehicle-km/year
International aviation	TAI	PJ/year
Domestic aviation	TAD	PJ/year
Freight rail transportation	TTF	PJ/year
Passengers rail transportation	TTP	PJ/year
Internal navigation	TWD	PJ/year
International navigation (bunkers)	TWI	PJ/year
Non-energy uses in transport	NEU	PJ/year
Residential segments* (11)		
Space heating	RH1, RH2, RH3, RH4	PJ/year
Space cooling	RC1, RC2, RC3, RC4	PJ/year
Hot water heating	RWH	PJ/year
Lighting	RL1, RL2, RL3, RL4	PJ/year
Cooking	RK1, RK2, RK3, RK4	PJ/year
Refrigerators and freezers	RRF	PJ/year
Cloth washers	RCW	PJ/year
Cloth dryers	RCD	PJ/year
Dish washers	RDW	PJ/year
Miscellaneous electric energy	REA	PJ/year
Other energy uses	ROT	PJ/year
Commercial segments* (8)		
Space heating	CH1, CH2, CH3, CH4	PJ/year
Space cooling	CC1, CC2, CC3. CC4	PJ/year
Hot water heating	CHW	PJ/year
Lighting	CLA	PJ/year
Cooking	CCK	PJ/year
Refrigerators and freezers	CRF	PJ/year
Electric equipments	COE	PJ/year
Other energy uses	COT	PJ/year
Agriculture segment (1)		
Agriculture	AGR	
Industrial segments (6)**		
Iron and steel	IIS	Millions tonnes
Non ferrous metals	INF	Millions tonnes
Chemicals	ICH	PJ
Pulp and paper	ILP	Millions tonnes
Non metal minerals	INM	PJ
Other industries	IOI	PJ
Other segment (1)		
Other non specified energy consumption	ONO	PJ/year

* RLi, RCi, RLi, RKi, CHi, CCi represent the demands for sub-regions available in some regions (eg.: USA, CAN).
** Industrial energy services are made up of a "recipe" of more detailed services: steam, process heat, machine drive, electrolytic service, other, and feedstock.

Overview of the TIMES attributes

Parameters associated with processes

Process-oriented parameters include *Technical parameters* (efficiency, availability factor(s), commodity consumptions per unit of activity, shares of fuels per unit activity, technical life of the process, construction lead time, dismantling lead-time and duration, amounts of the commodities consumed or released, etc), *Economic and policy parameters* (including a variety of costs, taxes or subsidies attached to the investment, dismantling, maintenance, and operation of a process, and process specific discount rates, also called *hurdle rate).* Finally, *Bounds* (upper, lower, equality) may be imposed on the investment, capacity, and activity of a process.

Parameters associated with commodities

Commodity-oriented parameters include *Technical parameters* (overall efficiency --for instance grid efficiency, and the time-slices over which that commodity is to be tracked. Additionally, for demand commodities, the annual projected demand and load curves if the commodity has a sub-annual time-slice resolution), *Economic parameters* (including additional costs, taxes, and subsidies on the production of a commodity. In the case of a demand service, an additional parameters is the demand's own-price elasticity), and *Policy based parameters* (bounds --at each period or cumulative, on production of a commodity, or on the imports or exports of a commodity by a region).

Parameters attached to commodity flows into and out of processes

Each flow in or out of a process has a variable attached to it, as well as several parameters: *Technical parameters* permit full control over the maximum and/or minimum share a given input or output flow may take within the same commodity group. For instance, a flexible turbine may accept oil or gas as input, and the modeler may use a parameter to limit the share of oil to at most 40% of the total fuel input. Other parameters and sets define the amount of certain outflows in relation to certain inflows (e.g., efficiency, emission rate by fuel, etc.). For instance, in an oil refinery a parameter may be used to set the total amount of refined products equal to 92% of the total amount of inputs into the refinery, or to calculate certain emissions as a fixed proportion of the amount of oil consumed. *Economic parameters* include delivery and other variable costs, taxes and subsidies attached to an individual process flow.

Parameters attached to the entire RES

These parameters include currency conversion factors (in a multi-regional model), region-specific time-slice definitions, region-specific values of capital and labor (influencing the costs of technologies), a region-specific general discount rate, and reference year for calculating the discounted total cost (objective function).

Managing and running a TIMES model (major enhancement)

The construction and maintenance of a TIMES database is greatly helped by the VEDA_FE (front end) interface that allows the user to construct, access, browse, and

generally maintain the model's database, as well as order a series of model runs. A companion back end interface, VEDA_BE, facilitates the exploration of the solution and the construction of result tables and graphics. The descriptions of the VEDA interfaces are available at http://www.kanors.com/software.htm

The TIMES database is transformed into a Linear Programming matrix via a computer program (matrix generator) written in the GAMS language. The LP is then solved by a commercial optimizer such as CPLEX or EXPRESS. When mixed integer programming (MIP) is required (see sections 5.1 and 5.2), the GAMS program automatically activates the MIP feature of the optimizer.

Economic rationale of TIMES

This section provides an economic interpretation of the TIMES and other partial equilibrium models based on maximizing total surplus. 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^* at price $p^*$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 explained below, when all markets are in equilibrium the total economic surplus is maximized.

Earlier and simpler Bottom-up models had fixed energy service demands, and thus were limited to minimizing the cost of supplying these demands (e.g. the early incarnations of MARKAL, see Fishbone and Abilock, 1981, Berger et al., 1992, though MARKAL has since been extended beyond these early versions). 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 feature is a fundamental step toward capturing the main feedback from the economy to the energy system.

The TIMES paradigm

In brief, TIMES is a technology explicit, multi-regional, partial equilibrium model, that assumes price elastic demands, competitive markets, and perfect foresight (resulting in Marginal value Pricing).

Multi-regional feature

The TIAM instance of TIMES covers the global energy system divided into 15 regional modules. The 15 individual regional modules are linked by energy and material trading variables, and by emission permit trading variables, if desired. The trade variables transform the set of regional modules into a single integrated multi-regional energy model, where actions taken in one region may affect all other regions.

Partial equilibrium properties

TIMES computes a partial equilibrium on energy markets. This equilibrium feature is present at every stage of the energy system: primary energy forms, secondary energy forms, and energy services. A supply-demand equilibrium has the property of maximizing the total surplus, defined as the sum of suppliers and consumers surpluses. The TIMES equilibrium possesses in fact three fundamental properties: *linearity*, *maximization of surplus*, and *competitiveness of energy markets*. These properties in turn result in two additional features: *marginal cost pricing*, and the *profit maximization* property. We briefly describe each property:

.

Linearity

A linear input-to-output relationship means that each technology may be implemented at any capacity, continuously from a lower limit to some upper limit, without economies of scale.

The fact that TIMES equations are linear, *does not mean that production functions behave in a linear fashion!* Indeed, the TIMES production functions are usually highly non-linear (but convex), representing non-linear functions as a stepped sequence of linear functions. As a simple example, a supply of some resource may be represented as a sequence of linear segments, each with rising unit cost. Thus, dis-economies of scale are frequently present in TIMES and are easily accommodated. The linearity property allows the TIMES equilibrium to be computed using Linear Programming..

Maximization of total surplus: Price equals Marginal value

The *total surplus* of an economy is the sum of the suppliers' and the consumers' surpluses. In TIMES, the suppliers of a commodity are technologies that procure a given commodity, and the consumers of a commodity are technologies or demands that consume a given commodity. The set of suppliers of a commodity is characterized by its *inverse production function* (or *supply curve*) plotting the marginal production cost of the commodity as a function of the quantity supplied. In TIMES, as in other technological models, the supply curve of a commodity is not explicitly specified, but rather implicitly *(endogenously)* derived by the model itself.

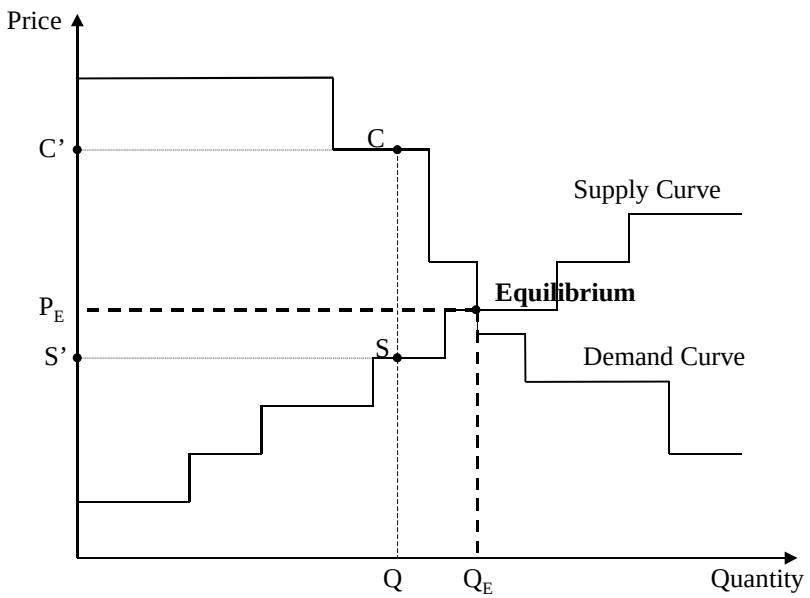

Figure 2. Equilibrium in the case of an energy form: the model implicitly constructs both the supply and the demand curves

In a symmetrical manner, each TIMES instance defines a series of *inverse demand functions* (i.e. *demand curves*). For demands, two cases are distinguished. First, if the commodity in question is an energy carrier whose production and consumption are endogenous to the model, then its demand curve is *implicitly constructed* within TIMES, and is a step-wise constant, decreasing function of the quantity demanded, as illustrated in Figure 2.

If on the other hand the commodity is a demand for an energy *service*, then its inverse demand curve is exogenously defined by the user via the specification of the own-price elasticity of that demand, and the curve is in this instance a smoothly decreasing curve as illustrated in Figure 3.[29] In TIMES, each energy service demand is assumed to have a constant own price elasticity function of the form: $\boldsymbol{D/D_0 = (P/P_0)^E}$, where $\{D_0, P_0\}$ is a reference pair of demand and price values for that energy service over the forecast horizon (obtained from solving a reference scenario), and $\boldsymbol{E}$ is the own price elasticity of that energy service demand chosen by the user (note that though not shown by the notation, this price elasticity may vary over time). Of course, the TIMES equilibrium concerns many commodities, and the equilibrium is a multi-dimensional analog of the above, where Q_E and P_E are now vectors rather than scalars.

It is seen from Figures 2 or 3 that the total surplus is maximized exactly when Q is equal to the equilibrium quantity Q_E. Therefore, we may state (in the single commodity case) the following Equivalence Principle:

"The supply-demand equilibrium is reached when the total surplus is maximized"

[29] This smooth curve will be discretized later for computational purposes.

In the multi-dimensional case, the proof of the above statement is less obvious, and requires a certain *integrability property* (Samuelson, 1952, Takayama and Judge, 1972). One sufficient condition for the integrability property to be satisfied is realized when the cross-price elasticities of any two energy forms are equal, viz.

$$\partial \boldsymbol{P_j} / \partial \boldsymbol{Q_i} = \partial \boldsymbol{P_i} / \partial \boldsymbol{Q_j} \quad \text{for all } \boldsymbol{i}, \boldsymbol{j}$$

In TIMES, it may be shown that the integrability property is always satisfied. Thus the equivalence principle is valid in all cases. This is a remarkably useful result that provides a simple method for computing the equilibrium via convex programming.

In summary, the equivalence principle guarantees that the TIMES supply-demand equilibrium maximizes total surplus. The total surplus concept has long been a mainstay of social welfare economics because it takes into account both the surpluses of consumers and of producers.[30]

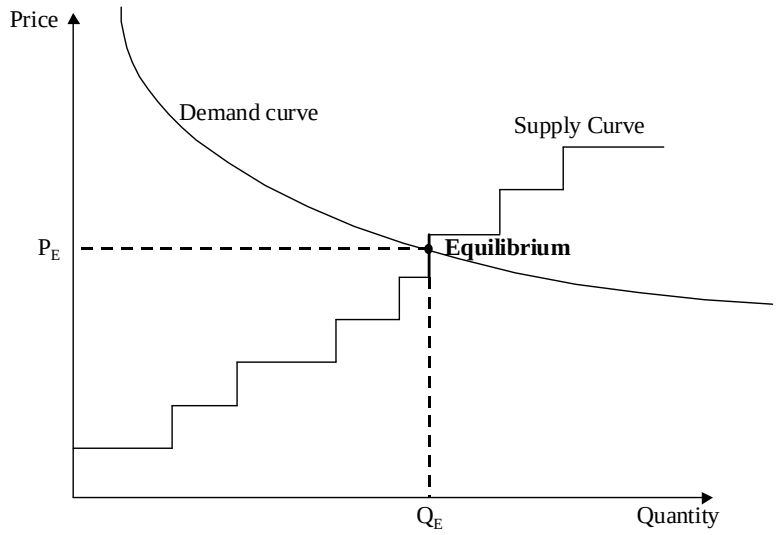

Figure 3. Equilibrium in the case of an energy service: the user explicitly provides the demand curve, usually using a simple functional form

Competitive energy markets with perfect foresight

Competitive energy markets are characterized by perfect information and by multiple agents that do not exercise market power. It is a standard result of microeconomic theory that the assumption of competitive markets entails that the market price of a commodity is equal to its marginal value in the economy. This property holds in the TIMES economy.

In TIMES, the perfect information assumption extends to the entire planning horizon, so that each agent has perfect foresight, i.e. complete knowledge of the market's parameters, present and future. Hence, the equilibrium is computed by

[30] See e.g. Samuelson, P, and W. Nordhaus (1977)

maximizing total surplus in one pass for the entire set of periods. Such a farsighted equilibrium is also called an *inter-temporal, dynamic* or *clairvoyant* equilibrium.

The perfect foresight assumption may be relaxed by assuming that some parameters are uncertain. This assumption is at the basis of the Stochastic Programming option of TIMES (see below). Other variants of TIMES assume that agents have a limited foresight (e.g. over one or a few periods rather than the full horizon).

Marginal value pricing

The fact that the TIMES equilibrium occurs at the intersection of the inverse supply and inverse demand curves implies directly that the equilibrium price is equal to the marginal system value of the commodity. From a different angle, the duality theory of Linear Programming indicates that for each constraint of the TIMES linear program there is a dual variable. This dual variable (when an optimal solution is reached) is also called the constraint's *shadow price*, and is equal to the marginal change of the objective function per unit increase of the constraint's right-hand-side. For instance, the shadow price of a demand constraint is the price of the corresponding energy service.

Three optional features of TIMES

The Lumpy Investment option

In some cases, the linearity property of the TIMES model may become a drawback for the accurate modeling of certain investment decisions. Consider for example a TIMES model for a relatively small community such as a city. For such a scope the *granularity* of some investments may have to be taken into account. For instance, the size of an electricity generation plant proposed by the model would have to conform to an implementable minimum size (it would make no sense to decide to construct a 50 MW nuclear plant). Another example for multi-region modeling might be whether or not to build cross-region electric grid(s) or gas pipeline(s) in discrete size increments. Processes subject to investments of only specific size increments are described as "lumpy" investments.

In such situations, Linear Programming is not adequate, and it is necessary to use Mixed Integer Programming (MIP) formulations and resolution techniques. MIP is an option embedded in the TIMES code.

Endogenous Technological Learning (ETL)

In a long-term dynamic model such as TIMES the characteristics of many of the future technologies are almost inevitably changing over the sequence of future periods due to *technological learning*.

In some cases it is possible to forecast such changes as a function of time, and thus to define a time-series of values for each parameter (e.g. unit investment cost, efficiency). In such cases, technological learning is *exogenous* since it depends only on time elapsed and may thus be specified via input parameters that changes over time.

In other cases there is evidence that the pace at which some technological parameters change is dependent on the *experience* acquired with this technology. Such

experience is not solely a function of time elapsed, but typically depends on the cumulative investment in the technology[31], as exemplified in the following formula:

$$INVCOST_t = a \cdot C_t^{-b}$$

Where C_t is the cumulative investment made in the technology, *INVCOST* is the unit investment cost, and *b* is related to the pace of learning.

In such a situation, technological learning is *endogenous*, since the future values of the parameters are no longer a function of time elapsed alone, but depend on the cumulative investment decisions taken by the model (which are themselves a model's result). Thus, the evolution of techno-economic parameters may no longer be established outside the model, since it depends on the model's results. ETL is also named *Learning-By-Doing* (LBD) by some authors.

Whereas exogenous technological learning does not require any additional modeling, endogenous technological learning (ETL) requires specific features. In TIMES, there is a provision to represent the effects of endogenous learning on the unit investment cost of technologies, using Mixed Integer Programming.

Stochastic Programming

Stochastic Programming is an approach for optimal decision making under risk. The risk consists of uncertainty regarding the values of some of the LP parameters (cost coefficients, matrix coefficients, RHS's). Each uncertain parameter is considered to be a random variable, usually with a discrete, known probability distribution. The objective function thus becomes a random variable and a criterion must be chosen in order to make the optimization possible. Such a criterion may be expected cost, expected utility, or others (Kanudia and Loulou, 1998).

Uncertainty on a given parameter is said to be *resolved* --either fully or partially, at the *resolution time*, i.e. the time at which the actual value of the parameter is revealed. Different parameters may have different times of resolution. Both the resolution times and the probability distributions of the parameters may be represented on an *event tree*, such as the one of figure 4, depicting a typical energy/environmental situation. In figure 4, two parameters are uncertain: mitigation level, and demand growth rate. The first may have only two values (High and Low), and becomes known in 2005. The second also may have two values (High and Low) and becomes known in 2010. The probabilities of the outcomes are shown along the branches. This example assumes that present time is 1995. This example is said to have three stages (i.e. two resolution times).

[31] It may also depend on R&D expenditures.

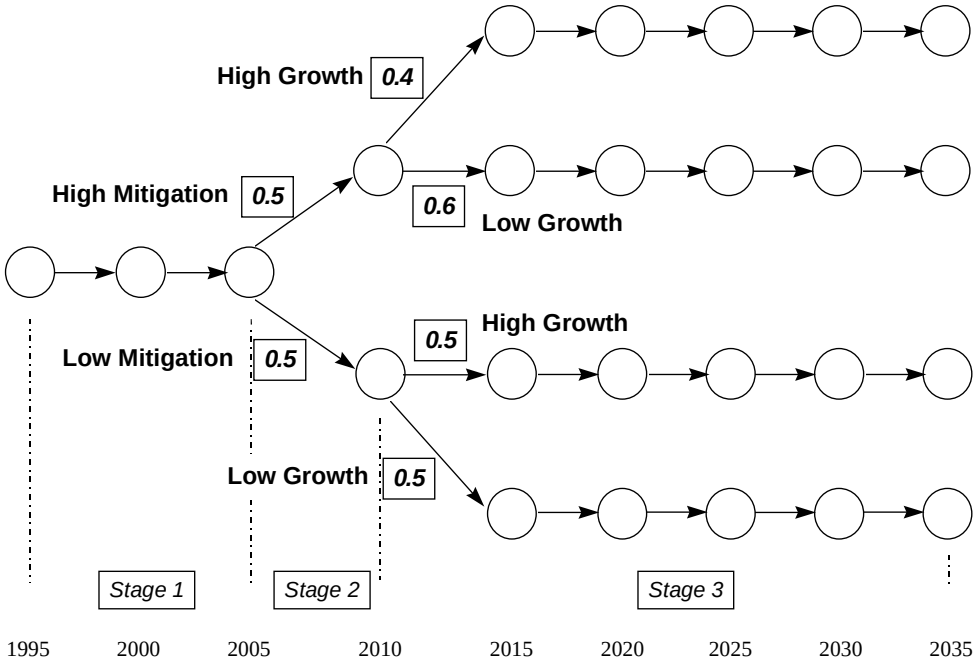

Figure 4. Example of an event tree

In TIMES, the resolution of Stochastic Programming allows the user two types of optimization criteria: Maximization of expected surplus or Maximization of Expected utility (consisting of a linear combination of expected surplus and a term expressing risk aversion).

The Climate Module of TIAM (major enhancement)

The Climate Module starts from global emissions of the three main GHG's generated by the TIAM global model, and proceeds to compute successively:
the changes in atmospheric concentrations ,
the changes in atmospheric radiative forcings from the three gases, and
the global temperature change in two layers.

The Climate Equations used to perform these calculations are in part adapted from Nordhaus and Boyer (1999) who proposed linear recursive equations for calculating concentrations and temperature changes. These linear equations give results that are good approximations of those obtained from more complex climate models (Drouet et al., 2004; Nordhaus and Boyer, 1999). The choice of the Nordhaus and Boyer's climate equations is motivated by the simplicity of their approach and by the fact that their climate module is well-documented and acceptably accurate. In our implementation, the single forcing equation has been replaced by three separate ones, and each has been linearized, via an approximation whose values closely approach the exact ones as long as the useful range is carefully selected.

The recent enhancement of the climate module has consisted in representing each of the three gases with each its own life cycle in the atmosphere. Then, a forcing formula is used (again separately for each gas) and finally the forcings of the three gases are added

to form the total radiative forcing of the entire set of gases modeled. The remaining (non modeled) gases are accounted for via an exogenous forcing quantity.*32*

We now describe the mathematical equations used at each of the three steps of the climate module.

Concentrations (accumulation of CO2, CH4, N2O)

CO2 concentration

CO2 accumulation is represented as the linear three-reservoir model below, adapted from Nordhaus and Boyer (1999): the atmosphere, the quickly mixing upper ocean + biosphere, and the deep ocean. CO2 flows in both directions between adjacent reservoirs. The 3-reservoir model is represented by the following 3 equations when the step of the recursion is equal to one year:

$$M_{atm}(y) = E(y-1) + (1 - \varphi_{atm-up})\, M_{atm}(y-1) + \varphi_{up-atm}\, M_{up}(y-1) \quad (1)$$

$$M_{up}(y) = (1 - \varphi_{up-atm} - \varphi_{up-lo})\, M_{up}(y-1) + \varphi_{atm-up}\, M_{atm}(y-1) + \varphi_{lo-up}\, M_{lo}(y-1) \quad (2)$$

$$M_{lo}(y) = (1 - \varphi_{lo-up})\, M_{lo}(y-1) + \varphi_{up-lo}\, M_{up}(y-1) \quad (3)$$

with

- $M_{atm}(y)$, $M_{up}(y)$, $M_{lo}(y)$: masses of CO_2 in atmosphere, in a quicly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively, at period t (GtC)
- E(y-1) = CO_2 emissions in previous year (GtC)
- φ_{ij}, transport rate from reservoir i to reservoir j (i, j = atm, up, lo) from year y-1 to y

CH4 concentration

CH4 accumulation is represented by a so-called single-box model in which the atmospheric methane concentration obeys the following equation:

$$CH4_{atm}(y) = \Phi_{CH4} \cdot \left(CH4_{atm}(y-1) + \tfrac{1}{d}\left(EN_{CH4}(y-1) + EA_{CH4}(y-1)\right)\right) \quad (1a)$$

where

[32] ***An alternative approach is also available in TIAM, consisting in first converting the emissions of each other (non CO2) GHG into a CO2-equivalent quantity, and to add these CO2-equivalents to form a fictitious emission of total CO2-equivalent, which is then treated as if it were a bona fide CO2 emission. The coefficients used for converting emissions of other gases into CO2-equivalents are the Global Warming Potentials (GWP) recommended by the IPCC AR4 (IPCC 2007).***

- $CH4_{atm}$, EN_{CH4}, and EA_{CH4}, are respectively: the atmospheric concentration, the natural emission and the anthropogenic emission of CH4 for year *y*, expressed in ppbv
- *d* is the density of *CH4*, expressed in *Gt/ppbv (d=2.84)*
- Φ_{CH4} is the one-year retention rate of CH4 in the atmosphere.

N2O concentration

N2O accumulation is also represented by a single-box model in which the atmospheric N2O concentration obeys the following equation:

$$N2O_{atm}(y) = \Phi_{N2O} \cdot \left(N2O_{atm}(y-1) + \frac{1}{d}(EN_{N2O}(y-1) + EA_{N2O}(y-1) \right) \qquad (1b)$$

where

- *N2O*, EN_{N2O}, and EA_{N2O}, are respectively: the atmospheric concentration, the natural emission and the anthropogenic emission of N2O for year y, expressed in ppbv
- *d* is the density of *N2O*, expressed in *Gt/ppbv (d=7.81)*
- Φ_{N2O} is the one-year retention rate of N2O in the atmosphere.

Radiative forcings

As already mentioned we assume that the forcings due to the various gases are additive (IPCC, 2007). Thus:

$$\Delta F(y) = \Delta F_{CO2}(y) + \Delta F_{CH4}(y) + \Delta F_{N2O}(y) + O(y) \qquad (4)$$

The four te4rms are calculated as follows:

Forcing from CO2

The relationship between CO2 accumulation and increased radiative forcing, $\Delta F_{CO2}(y)$, is derived from empirical measurements and climate models (IPCC 2007).

$$\Delta F_{CO2}(y) = \gamma * \frac{\ln(M_{atm}(y)/M_0)}{\ln 2} \qquad (4a)$$

where:

- M_0 (i.e.CO2ATM_PRE_IND) is the pre-industrial (circa 1750) reference atmospheric concentration of CO2 = 596.4 GtC
- γ is the radiative forcing sensitivity to atmospheric CO_2 concentration doubling = 3.7 W/m^2 (IPCC, 2007)

Forcing from CH4

The radiative forcing due to atmospheric CH4 is given by the following expression (IPCC, 2001, ch p.)

$$\Delta F_{CH4}(y) = 0.036 \cdot \left(\sqrt{CH4_y} - \sqrt{CH4_0}\right) - \left[f(CH4_y, N2O_0) - f(CH4_0, N2O_0)\right] \qquad (4b)$$

Forcing from N2O

The radiative forcing due to atmospheric N2O is given by the following expression (IPCC, 2001)

$$\Delta F_{N2O}(y) = 0.12 \cdot \left(\sqrt{N2O_y} - \sqrt{N2O_0}\right) - \left[f(CH4_0, N2O_y) - f(CH4_0, N2O_0)\right] \qquad (4c)$$

where:

$$f(x, y) = 0.47 \cdot \ln\left[1 + 2.01 \cdot 10^{-5} \cdot (xy)^{0.75} + 5.31 \cdot 10^{-15} \cdot x(xy)^{1.52}\right] \qquad (4d)$$

Note that the f(x,y) function, which quantifies the cross-effects on forcing of the presence in the atmosphere of both gases (CH4 and N2O), is not quite symmetrical in the two gases. As usual, the 0 subscript indicates the pre-industrial times (1750)

Forcing from other sources

O(y) is the increase in total radiative forcing at period t relative to pre-industrial level due to anthropogenic GHG's not represented explicitly in the model. Units = W/m^2. It is the modeler's responsibility to include in the calculation of O(y) only the forcing from those gases that are not modeled.

The parameterization of the three forcing equations (4a, 4b, 4c) is not controversial and relies on the results reported by Working Group I in the IPCC. IPCC (2001, Table 6.2, p.358) provides a value of 3.7 for γ. That same table provides the entire expressions for all three forcing equations.

In TIMES, each of the three forcing expressions is replaced by a linear approximation, in order to preserve linearity of the entire TIMES model. All three forcing expressions (4a, 4b, 4c) happen to be concave functions. Therefore, two linear approximations are obvious candidates. The first one is an approximation from below, consisting of the chord of the graph between two selected points. The second one has the same slope as the chord and is tangent to the graph, thus approximating the function from above. The final approximation is taken to be the arithmetic average of the two approximations. These linear expressions are easily derived once a range of interest is defined by the user, and remain very close to the accurate forcing values.

Temperature increase

In the TIMES Climate Module as in many other integrated models, climate change is represented by the global mean surface temperature. The idea behind the two-reservoir model is that a higher radiative forcing warms the atmospheric layer, which then quickly warms the upper ocean. In this model, the atmosphere and upper ocean form a single layer, which slowly warms the second layer consisting of the deep ocean.

$$\Delta T_{up}(y) = \Delta T_{up}(y-1) + \sigma_1\{ F(y) - \lambda\, \Delta T_{up}(y-1) - \sigma_2\, [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)]\} \quad (5)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y-1) + \sigma_3\, [\Delta T_{up}(y-1) - \Delta T_{low}\,(y-1)] \quad (6)$$

with

- ΔT_{up} = globally averaged surface temperature increase above pre-industrial level,
- ΔT_{low} = deep-ocean temperature increase above pre-industrial level,
- σ_1 = 1-year speed of adjustment parameter for atmospheric temperature (also known as the lag parameter),
- σ_2 = coefficient of heat loss from atmosphere to deep oceans,
- σ_3 = 1-year coefficient of heat gain by deep oceans,
- λ = feedback parameter (climatic retroaction). It is customary to write λ as $\lambda = \gamma/C_s$, C_s being the climate sensitivity parameter, defined as the change in equilibrium atmospheric temperature induced by a doubling of CO_2 concentration.

Remark: in contrast with most other parameters, the value of $\boldsymbol{C_s}$ is highly uncertain, with a possible range of values from 1°C to 10°C. This parameter is therefore a prime candidate for sensitivity analysis, or for treatment by probablilistic methods.

TIAM Data Base Improvements (major enhancements)

An important general review of the TIAM database was undertaken, and recently completed. Continuous enhancements are a normal maintenance task of any technological model, but the recent series of data modifications went much beyond regular maintenance, and concerned most sectors of the energy system. We give below a summary of the changes.

Emission trading mechanisms

In view of the simulation of various trading schemes, we have greatly enhanced the modeling options for representing various permit trading regimes, which now include the following cases:

- Single bubble, with full trading of all regions, resulting in fully efficient permit trading and a single permit price
- Single bubble, but for some sectors only (non covered sectors do not trade)
- Multiple bubbles, each with its own separate permit market (leading to multiple permit prices)
- Bubble with price cap: a bubble may decide to implement a permit trading market where GHG price is upper bounded by the regulator. In this case, the emission cap is not fully enforced (e.g. the Lieberman-Wagner bill now before the US senate)
- Banking and borrowing

Electric Power Generation sector (EPG)

This sector was almost completely revised. New data for solar, geothermal and hydro potentials were obtained, and more traditional technologies were also modified to reflect most recent available data. Table 2 shows the main data elements of the new database..

Table 2: EPG technologies in TIAM

Code	Name	vintages	Investment Cost	Operating cost	Efficiency
			$/kW	$/GJ elec	%
ECOAPUL105	EPLT: .G1.05.CON.COA.Pulverized Coal.	2003	1300	2.4	47.0%
ECOAPUL106	EPLT: .G1.05.CON.COA.Pulverized Coal.	2008	1300	2.4	47.0%
ECOAPUL107	EPLT: .G1.05.CON.COA.Pulverized Coal.	2018	1250	2.3	50.0%
ECOAPUL108	EPLT: .G1.05.CON.COA.Pulverized Coal.	2028	1150	2.2	52.0%
ECOACCO105	EPLT: .G1.05.ADV.COA.Oxygen Blown IGCC.	2003	1700	2.8	48.6%
ECOACCO106	EPLT: .G1.05.ADV.COA.Oxygen Blown IGCC.	2008	1700	2.8	48.6%
ECOACCO107	EPLT: .G1.05.ADV.COA.Oxygen Blown IGCC.	2018	1500	2.5	48.9%
ECOACCO108	EPLT: .G1.05.ADV.COA.Oxygen Blown IGCC.	2028	1475	2.5	54.0%
ECOACCA105	EPLT: .G1.05.ADV.COA.Air Blown IGCC.	2003	1450	2.5	46.6%
ECOACCA106	EPLT: .G1.05.ADV.COA.Air Blown IGCC.	2008	1450	2.5	46.6%
ECOACCA107	EPLT: .G1.05.ADV.COA.Air Blown IGCC.	2018	1250	2.2	46.9%
ECOACCA108	EPLT: .G1.05.ADV.COA.Air Blown IGCC.	2028	1225	2.2	52.0%
ECOAAFB105	EPLT:G1.05.ADV.COA.Atmospheric Fl Bed.	2003	1400	2.4	40.0%
ECOAAFB106	EPLT:G1.05.ADV.COA.Atmospheric Fl Bed.	2028	1400	2.4	45.0%
ECOAPFB105	EPLT:G1.05.ADV.COA.Pressurized Fl Bed.	2003	1500	2.6	47.0%
ECOAPFB105	EPLT:G1.05.ADV.COA.Pressurized Fl Bed.	2028	1500	2.6	46.0%
EOILSTE105	EPLT: .G1.05.CON.OIL.Oil Steam.	2003	950	1.4	35.0%
EOILSTE105	EPLT: .G1.05.CON.OIL.Oil Steam.	2008	950	1.4	40.0%
EGASSTE105	EPLT: .G1.05.CON.NGA.Gas Steam.	2003	950	1.4	35.0%

Code	Name	vintages	Investment Cost	Operating cost	Efficiency
			$/kW	$/GJ elec	%
EGASSTE105	EPLT: .G1.05.CON.NGA.Gas Steam.	2008	950	1.4	40.0%
EGOICCA105	EPLT: .G1.05.ADV.GOI.Gas/Oil Comb Cycle.	2003	600	1.0	57.0%
EGOICCA105	EPLT: .G1.05.ADV.GOI.Gas/Oil Comb Cycle.	2008	600	1.0	57.0%
EGOICCA105	EPLT: .G1.05.ADV.GOI.Gas/Oil Comb Cycle.	2018	550	0.9	61.0%
EGOICCA105	EPLT: .G1.05.ADV.GOI.Gas/Oil Comb Cycle.	2028	550	0.9	63.0%
EGOITUA105	EPLT: .G1.05.ADV.GOI.Advanced Gas/Oil Turbine.	2003	325	0.7	38.0%
EGOITUA106	EPLT: .G1.05.ADV.GOI.Advanced Gas/Oil Turbine.	2008	310	0.7	39.0%
EGOITUA107	EPLT: .G1.05.ADV.GOI.Advanced Gas/Oil Turbine.	2018	280	0.7	40.0%
EGASFCE105	EPLT: .G1.05.ADV.NGA.Fuel Cells.	2003	10500	16.3	48.0%
EGASFCE106	EPLT: .G1.05.ADV.NGA.Fuel Cells.	2008	6000	10.6	49.0%
EGASFCE107	EPLT: .G1.05.ADV.NGA.Fuel Cells.	2018	1300	4.7	50.0%
EGASFCE108	EPLT: .G1.05.ADV.NGA.Fuel Cells.	2028	1300	4.7	50.0%
ENUCADV105	EPLT: .G1.05.ADV.NUC.Advanced Nuclear.	2003	1700	4.3	-
ENUCADV106	EPLT: .G1.05.ADV.NUC.Advanced Nuclear.	2008	1700	4.3	-
ENUCLWR105	EPLT: .G1.05.ADV.NUC.Advanced Nuclear LWR.	2003	1500	3.9	-
ENUCLWR106	EPLT: .G1.05.ADV.NUC.Advanced Nuclear LWR.	2008	1500	3.9	-
ENUCPBM110	EPLT: .G1.10.ADV.NUC.Advanced Nuclear PBMR.	2008	1700	4.3	-
EOILGBL105	EPLT: .G1.05.CON.OIL.Generic Dist Gen for Base Load.	2003	599	4.2	31.0%
EOILGBL106	EPLT: .G1.05.CON.OIL.Generic Dist Gen for Base Load.	2008	599	4.2	37.0%
EOILGBL107	EPLT: .G1.05.CON.OIL.Generic Dist Gen for Base Load.	2003	538	6.6	32.1%
EOILGBL108	EPLT: .G1.05.CON.OIL.Generic Dist Gen for Base Load.	2008	538	6.6	32.5%
EBIOSLG105	EPLT: .G1.05.CON.BIO.Sld Biomass Gasification.	2003	1925	3.1	34.0%
EBIOSLG106	EPLT: .G1.05.CON.BIO.Sld Biomass Gasification.	2008	1925	3.1	34.0%
EBIOSLC105	EPLT: .G1.05.CON.BIO.Sld Biomass Direct Combustion.	2003	1700	4.9	32.8%
EBIOSLC106	EPLT: .G1.05.CON.BIO.Sld Biomass Direct Combustion.	2008	1700	4.9	32.8%
EBIOGAW105	EPLT: .G1.05.CON.BIO.Biogas from Waste.	2003	1900	4.3	32.8%
EBIOGAW106	EPLT: .G1.05.CON.BIO.Biogas from Waste.	2008	1900	4.3	32.8%
EBIOMSW105	EPLT: .G1.05.CON.BIO.MSW Direct Combustion.	2003	3500	6.6	32.8%
EBIOMSW106	EPLT: .G1.05.CON.BIO.MSW Direct Combustion.	2008	3500	6.6	32.8%
EHYDDAM105	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2003	1500	1.5	-
EHYDDAM106	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2008	1500	1.5	-
EHYDDAM107	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2018	1475	1.5	-
EHYDDAM108	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2028	1450	1.5	-
EHYDDAM109	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2038	1425	1.5	-
EHYDDAM110	EPLT: .G1.05.CON.HYD.Generic Impoundment Hydro.	2048	1400	1.4	-
EHYDDAM205	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2003	2500	1.8	-
EHYDDAM206	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2008	2500	1.8	-
EHYDDAM207	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2018	2438	1.8	-

Code	Name	vintages	Investment Cost	Operating cost	Efficiency
			$/kW	$/GJ elec	%
EHYDDAM208	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2028	2375	1.8	-
EHYDDAM209	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2038	2313	1.7	-
EHYDDAM210	EPLT: .G2.05.CON.HYD.Generic Impoundment Hydro.	2048	2250	1.7	-
EHYDDAM305	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2003	3500	2.1	-
EHYDDAM306	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2008	3500	2.1	-
EHYDDAM307	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2018	3413	2.1	-
EHYDDAM308	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2028	3325	2.1	-
EHYDDAM309	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2038	3238	2.0	-
EHYDDAM310	EPLT: .G3.05.CON.HYD.Generic Impoundment Hydro.	2048	3150	2.0	-
EHYDDAM405	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2003	4500	2.4	-
EHYDDAM406	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2008	4500	2.4	-
EHYDDAM407	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2018	4375	2.4	-
EHYDDAM408	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2028	4250	2.3	-
EHYDDAM409	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2038	4125	2.3	-
EHYDDAM410	EPLT: .G4.05.CON.HYD.Generic Impoundment Hydro.	2048	4000	2.3	-
EHYDDAM505	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2003	5500	2.7	-
EHYDDAM506	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2008	5500	2.7	-
EHYDDAM507	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2018	5375	2.7	-
EHYDDAM508	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2028	5250	2.7	-
EHYDDAM509	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2038	5125	2.6	-
EHYDDAM510	EPLT: .G5.05.CON.HYD.Generic Impoundment Hydro.	2048	5000	2.6	-
EHYDRUN105	EPLT: .G1.05.CON.HYD.Generic ROR Hydro.	2003	2000	2.8	-
EBIOCRG105	EPLT: .G1.05.CON.BIO.Crop Gasification.	2003	2000	6.4	32.8%
EBIOCRG106	EPLT: .G1.05.CON.BIO.Crop Gasification.	2008	2000	6.4	32.8%
EBIOCRC105	EPLT: .G1.05.CON.BIO.Crop Direct Combustion.	2003	1700	4.9	32.8%
EBIOCRC106	EPLT: .G1.05.CON.BIO.Crop Direct Combustion.	2008	1700	4.9	32.8%
EGEOT105	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2003	1750	1.1	-
EGEOT106	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2008	1700	1.1	-
EGEOT107	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2018	1650	1.0	-
EGEOT108	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2028	1600	1.0	-
EGEOT109	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2038	1550	1.0	-
EGEOT110	EPLT: .G1.05.CON.GEO.CEN.Shallow.	2048	1500	1.0	-
EGEOT205	EPLT: .G1.05.CON.GEO.CEN.Deep.	2003	2100	1.3	-
EGEOT206	EPLT: .G1.05.CON.GEO.CEN.Deep.	2008	2040	1.3	-
EGEOT207	EPLT: .G1.05.CON.GEO.CEN.Deep.	2018	1980	1.3	-
EGEOT208	EPLT: .G1.05.CON.GEO.CEN.Deep.	2028	1920	1.2	-
EGEOT209	EPLT: .G1.05.CON.GEO.CEN.Deep.	2038	1860	1.2	-
EGEOT210	EPLT: .G1.05.CON.GEO.CEN.Deep.	2048	1800	1.1	-

Code	Name	vintages	Investment Cost	Operating cost	Efficiency
			$/kW	$/GJ elec	%
EGEOT305	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2003	2500	1.6	-
EGEOT306	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2008	2420	1.5	-
EGEOT307	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2018	2340	1.5	-
EGEOT308	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2028	2260	1.4	-
EGEOT309	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2038	2180	1.4	-
EGEOT310	EPLT: .G1.05.CON.GEO.CEN.Very deep.	2048	2100	1.3	-
EWIND105	EPLT: .G1.04.CON.WIN.CEN.	2004	968	0.8	-
EWIND106	EPLT: .G1.04.CON.WIN.CEN.	2008	968	0.8	-
EWIND107	EPLT: .G1.04.CON.WIN.CEN.	2018	968	0.8	-
EWIND108	EPLT: .G1.04.CON.WIN.CEN.	2028	968	0.8	-
EWIND109	EPLT: .G1.04.CON.WIN.CEN.	2038	968	0.8	-
EWIND110	EPLT: .G1.04.CON.WIN.CEN.	2048	800	0.6	-
EWIND205	EPLT: .G1.10.CON.WIN.CEN.Offshore.	2008	1500	2.4	-
EWIND206	EPLT: .G1.10.CON.WIN.CEN.Offshore.	2018	1500	2.4	-
EWIND207	EPLT: .G1.10.CON.WIN.CEN.Offshore.	2028	1500	2.4	-
EWIND208	EPLT: .G1.10.CON.WIN.CEN.Offshore.	2038	1500	2.4	-
EWIND209	EPLT: .G1.10.CON.WIN.CEN.Offshore.	2048	1200	1.6	-
EWIND305	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2000	1100	1.0	-
EWIND306	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2008	1100	1.0	-
EWIND307	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2018	1100	1.0	-
EWIND308	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2028	1100	1.0	-
EWIND309	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2038	1100	1.0	-
EWIND310	EPLT: .G1.00.CON.WIN.DCN.Onshore.	2048	900	0.8	-
EWIND405	EPLT: .G1.10.CON.WIN.DCN.Onshore.	2008	1100	1.0	-
EWIND406	EPLT: .G1.10.CON.WIN.DCN.Onshore.	2018	1100	1.0	-
EWIND407	EPLT: .G1.10.CON.WIN.DCN.Onshore.	2028	1100	1.0	-
EWIND408	EPLT: .G1.10.CON.WIN.DCN.Onshore.	2038	1100	1.0	-
EWIND409	EPLT: .G1.10.CON.WIN.DCN.Onshore.	2048	900	0.8	-
ESOTH105	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2004	2500	0.8	-
ESOTH106	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2008	2200	0.8	-
ESOTH107	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2018	2050	0.8	-
ESOTH108	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2028	1850	0.8	-
ESOTH109	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2038	1790	0.8	-
ESOTH110	EPLT: .G1.04.CON.SOL.CEN.Thermal.	2048	1720	0.8	-
ESOPV105	EPLT: .G1.03.CON.SOL.CEN.PV.	2003	6500	6.3	-
ESOPV106	EPLT: .G1.03.CON.SOL.CEN.PV.	2018	2150	6.3	-
ESOPV107	EPLT: .G1.03.CON.SOL.CEN.PV.	2038	1700	3.2	-
ESOPV108	EPLT: .G1.03.CON.SOL.CEN.PV.	2048	1350	3.2	-
ESOPVD105	EPLT: .G1.05.CON.SOL.DCN.PV.	2003	10000	3.2	-
ESOPVD106	EPLT: .G1.05.CON.SOL.DCN.PV.	2023	3300	3.2	-
ESOPVD107	EPLT: .G1.05.CON.SOL.DCN.PV.	2033	2750	3.2	-
ESOPVD0105	EPLT: .G1.05.CON.SOL.DCN.PV.T0	2003	10000	3.2	-
ESOPVD0106	EPLT: .G1.05.CON.SOL.DCN.PV.T1	2023	3300	3.2	-
ESOPVD0107	EPLT: .G1.05.CON.SOL.DCN.PV.T2	2033	2750	3.2	-
ESOPVD1105	EPLT: .G1.05.CON.SOL.DCN.PV.T1	2003	10000	3.2	-
ESOPVD1106	EPLT: .G1.05.CON.SOL.DCN.PV.T2	2023	3300	3.2	-
ESOPVD1107	EPLT: .G1.05.CON.SOL.DCN.PV.T3	2033	2750	3.2	-
ESOPVD2105	EPLT: .G1.05.CON.SOL.DCN.PV.T2	2003	10000	3.2	-

Code	Name	vintages	Investment Cost	Operating cost	Efficiency
			$/kW	$/GJ elec	%
ESOPVD2106	EPLT: .G1.05.CON.SOL.DCN.PV.T3	2023	3300	3.2	-
ESOPVD2107	EPLT: .G1.05.CON.SOL.DCN.PV.T4	2033	2750	3.2	-
ESOPVD3105	EPLT: .G1.05.CON.SOL.DCN.PV.T3	2003	10000	3.2	-
ESOPVD3106	EPLT: .G1.05.CON.SOL.DCN.PV.T4	2023	3300	3.2	-
ESOPVD3107	EPLT: .G1.05.CON.SOL.DCN.PV.T5	2033	2750	3.2	-
ESOPVD4105	EPLT: .G1.05.CON.SOL.DCN.PV.T4	2003	10000	3.2	-
ESOPVD4106	EPLT: .G1.05.CON.SOL.DCN.PV.T5	2023	3300	3.2	-
ESOPVD4107	EPLT: .G1.05.CON.SOL.DCN.PV.T6	2033	2750	3.2	-
ESOPVD5105	EPLT: .G1.05.CON.SOL.DCN.PV.T5	2003	10000	3.2	-
ESOPVD5106	EPLT: .G1.05.CON.SOL.DCN.PV.T6	2023	3300	3.2	-
ESOPVD5107	EPLT: .G1.05.CON.SOL.DCN.PV.T7	2033	2750	3.2	-
ESOPV0105	EPLT: .G1.03.CON.SOL.CEN.PV.T0	2003	6500	0.3	-
ESOPV0106	EPLT: .G1.03.CON.SOL.CEN.PV.T1	2018	2150	0.3	-
ESOPV0107	EPLT: .G1.03.CON.SOL.CEN.PV.T2	2038	1700	0.3	-
ESOPV0108	EPLT: .G1.03.CON.SOL.CEN.PV.T3	2048	1350	0.3	-
ESOPV0109	EPLT: .G1.03.CON.SOL.CEN.PV.T4	2018	2150	0.3	-
ESOPV0110	EPLT: .G1.03.CON.SOL.CEN.PV.T5	2038	1700	0.3	-
ESOPV0111	EPLT: .G1.03.CON.SOL.CEN.PV.T6	2048	1350	0.3	-
ESOPV2105	EPLT: .G1.03.CON.SOL.CEN.PV.T2	2003	6500	0.3	-
ESOPV2106	EPLT: .G1.03.CON.SOL.CEN.PV.T3	2038	1700	0.3	-
ESOPV2107	EPLT: .G1.03.CON.SOL.CEN.PV.T4	2048	1350	0.3	-
ESOPV3105	EPLT: .G1.03.CON.SOL.CEN.PV.T3	2003	6500	0.3	-
ESOPV3106	EPLT: .G1.03.CON.SOL.CEN.PV.T4	2018	2150	0.3	-
ESOPV3107	EPLT: .G1.03.CON.SOL.CEN.PV.T5	2048	1350	0.3	-
ESOPV4105	EPLT: .G1.03.CON.SOL.CEN.PV.T4	2003	6500	0.3	-
ESOPV4106	EPLT: .G1.03.CON.SOL.CEN.PV.T5	2018	2150	0.3	-
ESOPV4107	EPLT: .G1.03.CON.SOL.CEN.PV.T6	2038	1700	0.3	-
ESOPV5105	EPLT: .G1.03.CON.SOL.CEN.PV.T5	2003	6500	0.3	-
ESOPV5106	EPLT: .G1.03.CON.SOL.CEN.PV.T6	2018	2150	0.3	-
ESOPV5107	EPLT: .G1.03.CON.SOL.CEN.PV.T7	2038	1700	0.3	-
ESOPV5108	EPLT: .G1.03.CON.SOL.CEN.PV.T8	2048	1350	0.3	-
ENUCFUS110	EPLT: .G1.05.ADV.NUC.Fusion Nuclear.	2008	3000	3.1	32.2%
ENUCFUS111	EPLT: .G1.05.ADV.NUC.Fusion Nuclear.	2008	3000	3.1	32.2%
EBIOSLGD05	EPLT: .G1.05.CON.BIO.Sld Biomass Gasification.Decentralized	2003	2000	6.4	32.8%
EBIOSLGD06	EPLT: .G1.05.CON.BIO.Sld Biomass Gasification.Decentralized	2008	2000	6.4	32.8%
EBIOSLCD05	EPLT: .G1.05.CON.BIO.Sld Biomass Direct Combustion.Decentralized	2003	1700	4.9	32.8%
EBIOSLCD06	EPLT: .G1.05.CON.BIO.Sld Biomass Direct Combustion.Decentralized	2008	1700	4.9	32.8%

Alternate energy production

The database for this sector was enhanced by the addition of 8 new technologies for the production of diesel fuel from various sources (biomass, coal, gas), of methanol, hydrogen, and ethanol. These technologies supplement the other production technologies already present in the model, with and without CO2 capture and storage (CCS, see below).

Technologies with CO2 capture and storage (CCS)

Five technologies were added to the database, as follows :

- Hydrogen production from coal, with CCS (2 technologies),
- Hydrogen production from natural gas with CCS
- Diesel production de diesel from natural gas with CCS,
- Methanol production de méthanol from natural gas with CCS.

Transportation sector

A complete review and modification of the road transport technologies was accomplished. This sub-sector comprises 8 segments:

- Automobiles,
- Light trucks,
- Commercial trucks,
- Medium trucks,
- Heavy trucks,
- Buses
- Three-wheelers,
- Two-wheelers

The first six segments were entirely revised as follows :

- Adjustment of certain costs, notably for alternative vehicles (alcool, hybrids, fuel cells from ethanol)
- Introduction of vintaged costs and efficeincies (2008, 2018, 2028, 2038, 2048)
- Introduction of a realistic tax for fossil fuels (gasoline, diesel, CNG, LPG)
- Adjustment of production costs for alcohols thanks to the new data on production technologies (see above)

Table 3 show the main parameters of automobles, as an important example. The other segments were similarly modeled.

Table 3 : Charactéristics of automobiles in TIAM

CODE	NAME	VINTAGE	INVCOST $/1000v-km	OPERATION COST $/1000km	EFFICIENCY 1000 v-km/GJ
TRTGCE005	CAR: .05.CFV.GAS.CAFE.STD.	2003	1038.47	62.31	0.35
TRTGCA005	CAR: .05.CFV.GAS.CAFE.STD.	2003	1150	23	0.34
TRTGCA010	CAR: .10.CFV.GAS.CAFE.STD.	2008	1150	23	0.37
TRTGCA020	CAR: .20.CFV.GAS.CAFE.STD.	2018	1150	23	0.41
TRTGCA030	CAR: .30.CFV.GAS.CAFE.STD.	2028	1150	23	0.44
TRTGCA040	CAR: .40.CFV.GAS.CAFE.STD.	2038	1150	23	0.48
TRTGCA050	CAR: .50.CFV.GAS.CAFE.STD.	2048	1150	23	0.51
TRTGCB005	CAR: .05.CFV.GAS.CAFE.3.5MPG.	2003	1210	24	0.39
TRTGCB010	CAR: .10.CFV.GAS.CAFE.3.5MPG.	2008	1210	24	0.43
TRTGCB020	CAR: .20.CFV.GAS.CAFE.3.5MPG.	2018	1210	24	0.48
TRTGCB030	CAR: .30.CFV.GAS.CAFE.3.5MPG.	2028	1210	24	0.53
TRTGCB040	CAR: .40.CFV.GAS.CAFE.3.5MPG.	2038	1210	24	0.58
TRTGCB050	CAR: .50.CFV.GAS.CAFE.3.5MPG.	2048	1210	24	0.63
TRTGCC005	CAR: .05.CFV.GAS.CAFE.7.0MPG.	2003	1225	25	0.44
TRTGCC010	CAR: .10.CFV.GAS.CAFE.7.0MPG.	2008	1225	25	0.48
TRTGCC020	CAR: .20.CFV.GAS.CAFE.7.0MPG.	2018	1225	25	0.54
TRTGCC030	CAR: .30.CFV.GAS.CAFE.7.0MPG.	2028	1225	25	0.59
TRTGCC040	CAR: .40.CFV.GAS.CAFE.7.0MPG.	2038	1225	25	0.65
TRTGCC050	CAR: .50.CFV.GAS.CAFE.7.0MPG.	2048	1225	25	0.70
TRTDCA005	CAR: .05.CFV.DST.CAFE.STD.	2003	1250	25	0.38
TRTDCA010	CAR: .10.CFV.DST.CAFE.STD.	2008	1250	25	0.42
TRTDCA020	CAR: .20.CFV.DST.CAFE.STD.	2018	1250	25	0.46
TRTDCA030	CAR: .30.CFV.DST.CAFE.STD.	2028	1250	25	0.49
TRTDCA040	CAR: .40.CFV.DST.CAFE.STD.	2038	1250	25	0.53
TRTDCA050	CAR: .50.CFV.DST.CAFE.STD.	2048	1250	25	0.57
TRTDCB005	CAR: .05.CFV.DST.CAFE.3.5MPG.	2003	1275	26	0.43
TRTDCB010	CAR: .10.CFV.DST.CAFE.3.5MPG.	2008	1275	26	0.47
TRTDCB020	CAR: .20.CFV.DST.CAFE.3.5MPG.	2018	1275	26	0.53
TRTDCB030	CAR: .30.CFV.DST.CAFE.3.5MPG.	2028	1275	26	0.58
TRTDCB040	CAR: .40.CFV.DST.CAFE.3.5MPG.	2038	1275	26	0.63
TRTDCB050	CAR: .50.CFV.DST.CAFE.3.5MPG.	2048	1275	26	0.69
TRTDCC005	CAR: .05.CFV.DST.CAFE.7.0MPG.	2003	1300	26	0.48
TRTDCC010	CAR: .10.CFV.DST.CAFE.7.0MPG.	2008	1300	26	0.53
TRTDCC020	CAR: .20.CFV.DST.CAFE.7.0MPG.	2018	1300	26	0.59
TRTDCC030	CAR: .30.CFV.DST.CAFE.7.0MPG.	2028	1300	26	0.65
TRTDCC040	CAR: .40.CFV.DST.CAFE.7.0MPG.	2038	1300	26	0.71
TRTDCC050	CAR: .50.CFV.DST.CAFE.7.0MPG.	2048	1300	26	0.77
TRTLPG005	CAR:.05.AFV.LPG.	2003	1170	23	0.34
TRTLPG010	CAR: .10.AFV.LPG.	2008	1170	23	0.37
TRTLPG020	CAR: .20.AFV.LPG.	2018	1170	23	0.41
TRTLPG030	CAR: .30.AFV.LPG.	2028	1170	23	0.44
TRTLPG040	CAR: .40.AFV.LPG.	2038	1170	23	0.48
TRTLPG050	CAR: .50.AFV.LPG.	2048	1170	23	0.51
TRTNGA005	CAR:.05.AFV.NGA.	2003	1350	27	0.34
TRTNGA010	CAR: .10.AFV.NGA.	2008	1350	27	0.37
TRTNGA025	CAR: .20.AFV.NGA.	2018	1350	27	0.41
TRTNGA030	CAR: .30.AFV.NGA.	2028	1350	27	0.44

CODE	NAME	VINTAGE	INVCOST $/1000v-km	OPERATION COST $/1000km	EFFICIENCY 1000 v-km/GJ
TRTNGA040	CAR: .40.AFV.NGA.	2038	1275	26	0.48
TRTNGA050	CAR: .50.AFV.NGA.	2048	1275	26	0.51
TRTMET005	CAR: .05.AFV.MET.	2003	1265	25	0.37
TRTMET010	CAR: .10.AFV.MET.	2008	1265	25	0.41
TRTMET020	CAR: .20.AFV.MET.	2018	1265	25	0.45
TRTMET030	CAR: .30.AFV.MET.	2028	1265	25	0.49
TRTMET040	CAR: .40.AFV.MET.	2038	1265	25	0.52
TRTMET050	CAR: .50.AFV.MET.	2048	1265	25	0.56
TRTETH005	CAR: .05.AFV.ETH.	2003	1265	25	0.34
TRTETH010	CAR: .10.AFV.ETH.	2008	1265	25	0.37
TRTETH020	CAR: .20.AFV.ETH.	2018	1265	25	0.41
TRTETH030	CAR: .30.AFV.ETH.	2028	1265	25	0.44
TRTETH040	CAR: .40.AFV.ETH.	2038	1265	25	0.48
TRTETH050	CAR: .50.AFV.ETH.	2048	1265	25	0.51
TRTETA005	CAR: .05.AFV.ETH.10%MPG	2003	1265	25	0.39
TRTETA010	CAR: .10.AFV.ETH.10%MPG	2008	1265	25	0.43
TRTETA020	CAR: .20.AFV.ETH.10%MPG	2018	1265	25	0.48
TRTETA030	CAR: .30.AFV.ETH.10%MPG	2028	1265	25	0.53
TRTETA040	CAR: .40.AFV.ETH.10%MPG	2038	1265	25	0.58
TRTETA050	CAR: .50.AFV.ETH.10%MPG	2048	1265	25	0.63
TRTETB005	CAR: .05.AFV.ETH.20%MPG	2003	1265	25	0.44
TRTETB010	CAR: .10.AFV.ETH.20%MPG	2008	1265	25	0.48
TRTETB020	CAR: .20.AFV.ETH.20%MPG	2018	1265	25	0.54
TRTETB030	CAR: .30.AFV.ETH.20%MPG	2028	1265	25	0.59
TRTETB040	CAR: .40.AFV.ETH.20%MPG	2038	1265	25	0.65
TRTETB050	CAR: .50.AFV.ETH.20%MPG	2048	1265	25	0.70
TRTELC005	CAR: .05.AFV.ELC.	2003	1742	35	0.55
TRTELC010	CAR: .10.AFV.ELC.	2008	1725	35	0.67
TRTELC020	CAR: .20.AFV.ELC.	2018	1708	34	0.78
TRTELC030	CAR: .30.AFV.ELC.	2028	1691	34	0.86
TRTELC040	CAR: .40.AFV.ELC.	2038	1691	34	0.93
TRTELC050	CAR: .50.AFV.ELC.	2048	1691	34	1.01
TRTHYB005	CAR: .05.AFV.HYB.	2003	1800	46	0.52
TRTHYB010	CAR: .10.AFV.HYB.	2008	1600	42	0.64
TRTHYB020	CAR: .20.AFV.HYB.	2018	1500	38	0.74
TRTHYB030	CAR: .30.AFV.HYB.	2028	1300	34	0.82
TRTHYB040	CAR: .40.AFV.HYB.	2038	1250	29	0.88
TRTHYB050	CAR: .50.AFV.HYB.	2048	1225	25	0.96
TRTFUC010	CAR: .10.AFV.FUC. ETH	2008	1600	120.00	0.74
TRTFUC020	CAR: .20.AFV.FUC. ETH	2018	1500	70.00	0.82
TRTFUC030	CAR: .30.AFV.FUC. ETH	2028	1300	55.00	0.88
TRTFUC040	CAR: .40.AFV.FUC. ETH	2038	1250	45.00	0.96
TRTFUC050	CAR: .50.AFV.FUC. ETH	2048	1225	30.00	0.96

Légende:	ETH=Ethanol
GAS=Essence	FC=Pile à Combustible
DST= Diesel	

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6. PEM-TEAMS (USTUTT)

The Pan-European TIMES model has been updated according latest European statistics (EUROSTAT 2005).
In the public electricity and heat generation sector additional advanced fossil electricity generation technologies have been implemented. E.g. Oxyfuel processes for different fuel types have been inserted taking into account that different demonstration project in Europe have been started. The model incorporates differences in capture efficiency among the CCS technologies (higher capture efficiencies for Oxyfuel than for IGCC).
Additional enlargements have also been made for the renewable technology portfolio. The number of renewable CHP plants and Biomass plants with CCS has been inserted in the model.
In the matter of renewable energy use, the country potentials have been revised and especially biomass potentials have been detailed by different types of biomass energy carriers and land use.
In the transport sector the fuel flexibility of aviation has been increased. The conventional aviation fuels kerosene and gasoline can now be substituted by synthetic fuels that can be produced either from biomass (BTL), coal (CTL) or natural gas (GTL). Furthermore growth constraints have been introduced in the transport sector that relates the maximum possible investment in alternative vehicle technologies to the already installed capacity in the previous model period. This assures that alternative vehicle technologies cannot penetrate the market abruptly but are introduced more slightly. Growth constraints similar to those in the transport sector have also been created for alternative fuel production technologies. The aim was to model the fact that new fuel production technologies usually enter the market in the form of smaller pilot projects first before becoming available on a larger scale.
In the residential and commercial sectors most of the improvements are related to technologies for space heating, water heating, space cooling and the potential of energy savaging potential has been updated. One enhancement for example was the introduction of absorption chillers that produce space cooling from district heat. Furthermore the availabilities of all space heating technologies have been adopted for each region according to the country specific heating degree days. The availabilities of technologies for space cooling have been adjusted similarly. For dual technologies with two output commodities (e.g. space heating and water heating) the output shares were matched to the actual shares of the useful energy demand for these commodities in each region.
Moreover new potentials for the extension of district and local heating grids in the commercial and residential sector have been implemented. For each region the district and local heating potential has been modeled via four steps. The different steps represent different extension options of district and local heating grids depending on the useful heat demand density in the rual and urban areas in the different European countries. The steps are characterized by different specific investment costs and a given potential.

7. DEMETER (UNIMAN)

There are two main model enhancements. The first concerns the inclusion of carbon leakage from sequestration reservoirs (also referred to as seepage). In a previous work (Gerlagh R. and B.C.C. van der Zwaan 2006, "Options and Instruments for a Deep Cut in CO2 Emissions: Carbon Capture or Renewables, Taxes or Subsidies?", The Energy Journal, 27:25-48), we abstracted from carbon leakage. We have now included two forms of leakage in the model: exponential and delayed. Exponential leakage implies that each year, a constant share of total sequestered carbon dioxide leaks back into the atmosphere. Delayed leakage means that the carbon leakage only starts after a certain period of time. We have carried out calculations for a series of scenarios with different leakage rates to establish the sensitivity of the optimal use of CCS with respect to this leakage phenomenon. We have found that CCS remains an important instrument to cap atmospheric carbon dioxide concentrations during the 21st century, even if the sequestered carbon dioxide leaks back after – on average – hundred years.

The second model enhancement is more difficult, and is beign implemented. It is our aim to adjust the model such that it can be used for studying the consequences of uncertainty with respect to climate sensitivity and/or carbon leakage on optimal short-run emission reduction policy. Preliminary calculations with a stripped down model version have been successful, but to make this enhancement for the full model requires an elaborate and tedious writing of modeling source code that is yet unfinished, but will before the start of the stochastic analysis contained in WP6.

8. GEMINI-E3 (ORDECYS)

GEMINI-E3 Model Enhancements

June 2008

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Abstract

This document presents the most recent improvements for GEMINI-E3 done as part of the PLANETS EU-project.

Contents

1 Introduction **2**

2 A new classification **3**

3 A new database **6**

4 Equations for temperature increase **8**

5 A new representation for electricity generation **10**
5.1 Investment decision 10
5.2 Carbon Capture and Sequestration 12

6 A new web interface **12**

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1 Introduction

This document reports on the improvements and updates done to the GEMINI-E3 model. GEMINI-E3 is the name of the first Computable General Equilibrium Model developed jointly by the French Ministry of Equipment and the French Atomic Energy Agency. The team now benefits from a nearly 15 year experience in CGE modeling, associated with a close collaboration with the main research teams working in the field of climate change policy and with a participation to the political debate on this topic. GEMINI-E3, which is the fifth version, is currently a family of general equilibrium models, all of them multi-sector and dynamic, but some being multi-country and some purely domestic or aimed at domestic policy assessment purposes[1]. The original version of the multi-country model is fully described in [4]. Several successive versions have been developed, with an increasing number of countries/regions (from 3 to 28) and an increasing number of sectors (from 8 to 18). A more detailed representation of countries and sectors was required by recent assessment works, from very global ones such as the Kyoto Protocol to more precise ones such as the European Trading System implemented from the start of 2005. In brief, the recent uses of the model have been directed toward:

- analyzing the implementation of economic instruments for greenhouse gases (GHG) emissions in a second-best setting [8];
- assessing the strategic allocation of greenhouse gases emission allowances in the EU-wide market [12];
- assessing and comparing regional welfare costs associated with alternative multi-gas strategies for a stabilization of global greenhouse gases emissions in the long run [13];
- analyzing the behavior of Russia in the Kyoto Protocol [1, 2];
- assessing the economic impact of the US withdrawal from the Kyoto Protocol [9];
- analyzing the French Climate policy formulated under the Kyoto Protocol [5, 6];
- assessing the economic impact of a French nuclear moratorium with respect to the Kyoto Protocol [7];
- assessing the cost of the Kyoto Protocol for Switzerland with and without international emissions trading [11];
- assessing the double dividend hypothesis of climate change policy, with due consideration to preexisting tax distortions in factor markets for the Swiss economy [10];
- assessing the effects of the increase of oil prices on global and regional GHG emissions [32].

We use in the PLANETS project the fifth version of the GEMINI-E3 model. Compared to the fourth version several improvements were done :

1. A new classification is adopted allowing one to describe more regions and more goods;
2. The reference year of the model is updated. The model is now calibrated on the year 2001 instead of 1997 and the database is completely rebuild;
3. We have included in this new version a block of equations which computes the temperature increase;

[1] GEMINI-E3 France [5, 6], GEMINI-E3 Switzerland [11], GEMINI-E3 Tunisia [3].

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4. The electricity sector has been enhanced to handle nuclear and renewable power plants explicitly and carbon capture and sequestration (CCS) technology.
5. A new GEMINI-E3 web interface is available to explore the assessment of world climate policies.

These improvements are detailed in the next sections.

2 A new classification

The fifth version of GEMINI-E3 describes 28 countries/regions instead of 21 in the previous version, and 18 sectors/goods instead of 14. This new classification is given in table 1. The nomenclature that has been chosen allows to individualize the main economic countries/regions and GHG emitters. Table 2 gives for the countries and the regions represented in the model their shares in the world population and the world GDP, and in the global GHG emissions. Except the two biggest economies (US and Japan) and the two highest emitters (US and China), no country or region has a bigger than 10% share either in the world economy or in the GHG emissions.

Concerning sectors and goods as it was done in all economic models applied to energy and climate change policies, we distinguish 5 energy goods and sectors (Coal, Crude Oil, Natural Gas, Refined Petroleum Product and Electricity). We try to describe the main energy intensive sectors (Mineral Products, Chemical Products, Metal Products, Paper Products) and we isolate three sectors concerning transport activities (Sea Transport, Air Transport and Other Transport). The 6 remaining sectors and goods are Forestry, Agriculture, Consuming Goods, Equipment Goods, Services and Dwelling.

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Table 1: Dimensions of the GEMINI-E3 model

Countries or Regions		**Sectors**
Annex B		***Energy***
Germany	DEU	01 Coal
France	FRA	02 Crude Oil
United Kingdom	GBR	03 Natural Gas
Italy	ITA	04 Refined Petroleum
Spain	ESP	05 Electricity
Netherlands	NLD	***Non-Energy***
Belgium	BEL	06 Agriculture
Poland	POL	07 Forestry
Rest of EU-25	OEU	08 Mineral Products
Switzerland	CHE	09 Chemical Rubber Plastic
Other European Countries	XEU	10 Metal and metal products
United States of America	USA	11 Paper Products Publishing
Canada	CAN	12 Transport n.e.c.
Australia and New Zealand	AUZ	13 Sea Transport
Japan	JAP	14 Air Transport
Russia	RUS	15 Consuming goods
Rest of Former Soviet Union	XSU	16 Equipment goods
Non-Annex B		17 Services
China	CHI	18 Dwellings
Brazil	BRA	
India	IND	***Household Sector***
Mexico	MEX	
Venezuela	VEN	***Primary Factors***
Rest of Latin America	LAT	Labor
Turkey	TUR	Capital
Rest of Asia	ASI	Energy
Middle East	MID	Fixed factor (sector 01-03)
Tunisia	TUN	Other inputs
Rest of Africa	AFR	

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Table 2: Countries and regions represented in GEMINI-E3 - Structural Data in 2001

Countries or regions	Population[a]	GHG emissions[b]	GDP[c]	%Pop.	%GHG	%GDP
DEU	82.3	310	1 889	1.4%	3.2%	6.0%
FRA	59.3	160	1 347	1.0%	1.6%	4.3%
GBR	58.7	205	1 427	1.0%	2.1%	4.5%
ITA	57.7	157	1 113	1.0%	1.6%	3.5%
ESP	40.7	107	583	0.7%	1.1%	1.9%
NLD	15.9	105	400	0.3%	1.1%	1.3%
BEL	10.3	54	240	0.2%	0.6%	0.8%
POL	38.6	102	178	0.6%	1.0%	0.6%
OEU	88.4	250	1 190	1.5%	2.6%	3.8%
CHE	7.2	15	236	0.1%	0.2%	0.8%
USA	284.2	1938	10 335	4.7%	19.9%	32.8%
JAP	127.0	376	4 159	2.1%	3.9%	13.2%
XEU	55.8	130	326	0.9%	1.3%	1.0%
CAN	30.7	479	711	0.5%	4.9%	2.3%
AUZ	22.9	186	417	0.4%	1.9%	1.3%
TUR	68.2	90	153	1.1%	0.9%	0.5%
RUS	146.6	489	300	2.4%	5.0%	1.0%
XSU	120.6	327	106	2.0%	3.4%	0.3%
CHI	1274.0	1278	1 293	21.0%	13.1%	4.1%
IND	1021.1	429	463	16.8%	4.4%	1.5%
ASI	957.5	793	1 473	15.8%	8.1%	4.7%
BRA	173.9	244	497	2.9%	2.5%	1.6%
VEN	24.4	94	128	0.4%	1.0%	0.4%
LAT	224.6	322	735	3.7%	3.3%	2.3%
MEX	100.1	170	611	1.6%	1.7%	1.9%
MID	167.9	347	636	2.8%	3.6%	2.0%
TUN	9.6	34	20	0.2%	0.3%	0.1%
AFR	802.9	550	520	13.2%	5.6%	1.7%
World	6071.0	9742	31 488	100.0%	100.0%	100.0%

[a] million of inhabitants
[b] million tonnes of carbon-equivalent
[c] billion 2001 US$ using exchanges rates

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3 A new database

The building and the calibration of a CGE model rest on economic and energy data that are usually contained in comprehensive databases, specifically established for this purpose. The present version of GEMINI-E3 is built on GTAP-6 [16], a database that accommodates a consistent representation of energy markets in physical units as well as detailed socio-accounting matrices (SAM) [27] for a large set of countries or regions and bilateral trade flows.

A Social Accounting Matrix (SAM) [17] can be interpreted as a complete description of the entire market transactions of commodities and primary factors made by the agents within an economy. A SAM describes also the transfers of revenues between agents (for example, social benefits payed by the government to households). A SAM is founded on the principle of balance between expenses (in columns) and the receipts (in lines) on the level of each account, but also on the level of the whole accounts. In this way a SAM is based on the Walras' law in which all markets are balanced. The building of a SAM required to compile different statistical data and to reconcile these alternative sources. The SAM is now widely used in economic modeling and in particular in Computable General Equilibrium models. The SAM used in the GEMINI-E3 model takes into account three agents (or institutions) : Households, Government and Foreign (or Rest Of the World). Note that firms in GEMINI-E3 are not considered as an agent, even if the production accounts are described for the 18 sectors, because we suppose that firms are owned by households who received the remuneration of capital and the rents of fix factors.

The figure 1 presents the general structure of the SAM used in GEMINI-E3. This SAM is constituted of seven blocks :

- An intermediate consumption matrix, which gives for each sector the intermediate consumption in the 18 goods;
- A domestic final uses block, which describes the households consumption, the government consumption and the investment in the 18 goods;
- An external trade block, which gives the imports and exports;
- An indirect taxation block which describes the taxes collected on household consumption, on value added components (social security contribution on labor, tax on operating surplus), on external trade (imports duties and export subsidies), on intermediate consumption, etc.
- A transfer revenue matrix, which describes the transfer of revenue between agents (household, government and foreign (or ROW));
- finally, a saving block which computes the saving of each agent which the sum is equal to the total investment.

The GTAP database is completed by other information especially on indirect taxation and government expenditures, mainly coming from International Energy Agency [22, 21, 20], OECD [26, 25] and International Monetary Fund [23]. An important work must be done in order to harmonize all these sources of information. The result is for each country or region a consistent Social Accounting Matrix in the form described in the figure 2. Let us recall that the GTAP 6 database is relative to the year 2001 which is the base year of the model. Concerning data on population we use the work done by the United Nations [30]. We retain the *medium variant* projection. Table 3 gives in a schematic way the different assumptions underlying the projection variants proposed by the United Nations.

In the present version, that is capitalizing on participation in the EMF Working Group 21 [33, 34, 29, 15, 28, 14], the model has been updated in order to fully integrate all GHG

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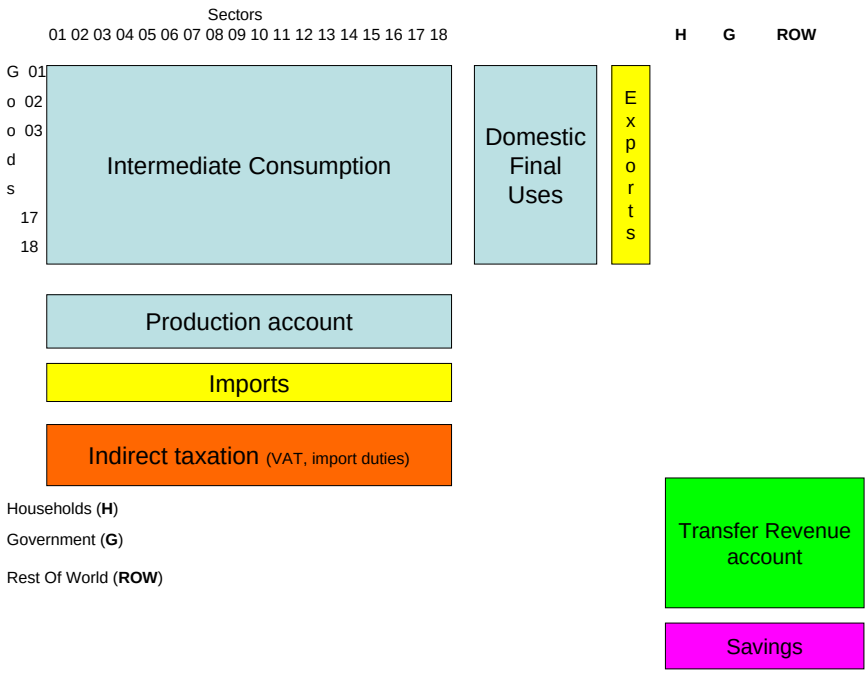

Figure 1: Structure of a Social Accounting Matrix

Table 3: Population projection assumptions (source : [30])

	Assumptions		
Projection variant	*Fertility*	*Mortality*	*International migration*
Low	Low	Normal	Normal
Medium	Medium	Normal	Normal
High	High	Normal	Normal
Constant-fertility	Constant	Normal	Normal
Constant-mortality	Medium	Constant	Normal
Zero-migration	Medium	Normal	Zero

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emissions[2]. For non-CO_2 greenhouse gases, data on emissions and abatement costs come from the U.S. Environmental Protection Agency [31]. We take into account all the direct GHGs covered by the United Nations Framework Convention on Climate Change : methane, nitrous oxide, and the high global warming potential (GWP) gases. Emissions of non carbon greenhouse are converted to a CO_2-equivalent basis using the 100-year GWPs defined by the Intergovernmental Panel on Climate Change [19].

4 Equations for temperature increase

We present the equations to compute the temperature increase from the world total emissions of CO_2, CH_4 and N_2O. They are based on the climate module of the MERGE model version 5.2 [24]. Climate is represented by a simple model which simulates the life duration of the CO_2, CH_4 and N_2O gas in the atmosphere. The fluorescent gas effect is exogenous. The equations compute the global radiative forcing, the global temperature at the equilibrium (ie, if the chemical structure would remain constant) and the actual temperature.

CO_2 emissions are send into five physical sinks. Equation (1) describes the decay of the CO_2 stock in each sink $b = 1, \ldots, 5$. The coefficients $d1$ et $d2$ defines the gas life duration.

$$CO2_{b,t+1} - \frac{d2_{t,b}}{2} T^E_{\mathrm{CO_2},t+1} = CO2_{b,t} d1^n_b + \frac{d2_{t,b}}{2} T^E_{\mathrm{CO_2},t}. \tag{1}$$

The total of CO_2 ($S_{\mathrm{CO_2},t}$) is the sum of the CO_2 concentrations in the five sinks.

$$S_{\mathrm{CO_2},t} = \sum_b CO2_{b,t} + nco2 \tag{2}$$

Equation (3) describes the decay of the others GHGs (ie $g \in \mathsf{G} - \{\mathrm{CO_2}\}$) in the atmosphere. $s0_g$ represents the 2000 stock of gas g. The quantity of gas in the atmosphere is S.

$$SM_{g,t+1} - \frac{od2_{t,g}}{2} TEM_{g,t+1} = SM_{g,t} od1^n_g + \frac{od2_{t,g}}{2} TEM_{g,t} \tag{3}$$

$$S_{g,t} = SM_{g,t} + s0_g \tag{4}$$

The temperature at equilibrium (PT) is determined by the accumulation of the GHG in the atmosphere. It is proportional to the aggregated radiative forcing computed by all gases. For CO_2, the radiative forcing is proportional to the logarithm of the ratio of the actual level over the initial level. For CH_4 and N_2O, the calculation is more complex; the radiative forcing of CH_4 is depending on N_2O and reciprocally, as defined in [18]. Here this relation is simplified by a linear form. The fluorescent gas radiative effect (f_f) is exogenous like the cooling effect from sulfur (c_t).

$$\begin{aligned} PT_t = \; & f_m \Big(f_a + f_{\mathrm{CO_2}} \cdot \ln(S_{\mathrm{CO_2},t}/bs_{\mathrm{CO_2}}) \\ & + \sum_{g \neq \mathrm{CO_2}} inter_g \cdot f_g \cdot (sm_g \cdot S^r_{g,t} - sm_g \cdot bs^r_g) \\ & + f_f \Big) \\ & - c_t \end{aligned} \tag{5}$$

[2]A version of the model taking into account only carbon emissions has been kept for special applications.

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France US $ Millions	Coal	Oil	Gas	Petroleum Products	Electricity	Agriculture	Forestry	Mineral Products	Chemical, rubber, Plastic	Metal and Metal products	Paper products publishing	Transport nec	Sea Transport	Air Transport	Consuming goods	Equipment goods	Services	Dwellings	Total	Investment	Household Consumption	Government consumption	Export	Total Uses
Coal	0.4	0	0	4235	313.5	0	0	22.9	10.6	12.6	8.1	0	0	0	23.1	7.6	4.2	0	612.5	0	90.7	0	0.4	1828.6
Oil	0	0	0	11423.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas	15.2	0	35.9	602	305.7	4.18	0.2	230.3	590	135.5	178.9	0.7	1.7	361.8	2384	1141.1	0	0	1384.7	0	221.4	0	4.4	5620.5
Petroleum Products	0	0	0	2381.8	224.4	43.13	8.5	304.6	183.64	211.5	35.2	78.54	195.9	16.7	168.7	722	10.97	0	1324.9	0	3456.8	0	2649	9594.7
Electricity	24.7	0	12.9	2048	305.7	0.29	0.6	101.7	159.9	20.41	10.3	0.7	1.7	10.15	1108.5	1064.6	0.12	0	3394.7	0	3105.5	0	3105.5	9705.7
Agriculture	0	0	48.3	238.8	118	5104.4	46.4	80.7	16.93	19.9	19.9	154	39.3	23.82	3561	2914.6	1.5	0	12324.9	0	1756.6	0	23	20080.2
Mineral Products	0	0	0	1.8	0.6	230	7.1	3.7	0.4	0.6	0.6	0.1	0.1	0.4	204.4	1699	0	3.6	2288.5	0	941.3	4.9	315.1	5710.8
Forestry	0	0	0	0	0.1	0.6	7.6	6.2	0.1	0.1	2.8	0.7	0.7	2.1	23232	14822.7	1.6	0.6	38364.2	0	23	0.2	6992.9	45022.8
Metal and Metal products	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	708.5	2012.2	0.1	0.1	2788.5	0	1668.1	2.1	315.1	4773.8
Paper products publishing	0	0	0	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	2214.2	3806.4	0.1	0.1	6023.7	0	3456.8	0.2	6992.9	16536.7
Transport nec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sea Transport	1.9	0	2.4	9.8	116.7	297	14.5	271.5	25003	1315.5	1545.4	211	542	7.12	2135.5	2018	21.97	36.9	31787.2	0	3456.8	0.3	3105.5	39453.7
Air Transport	0	0	0.2	5.1	0.2	4.72	1.5	4.72	37011	218	428.2	67.53	121.5	2956.8	2527.3	8140	25187.8	8.1	41177.5	0	1668.1	0.1	1756.6	75.7
Consuming goods	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1
Equipment goods	0.1	0.2	1.6	2.2	12.8	113	14.7	72.2	3.6	14.6	9.47	9.92	1.92	103.1	28898.9	14695.2	0	0	43933	0	3456.8	0	3105.5	75.7
Services	0.1	0.2	1.6	1.0	15.6	1.0	0.6	10.7	1.3	35.6	566.8	53.1	1191	112	1108.5	1064.6	0.12	0	5104.4	0	1756.6	0	3105.5	11.8
Dwellings	0.1	0.2	5.1	9.8	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1
Total	111.5	96.6	112.7	15494.3	1130.2	5323.2	2037	415.3	1651	2151.8	5422	796.1	3030.4	3914	3305.9	2771.9	7585	6013.3	5383.4	918.8	1220.7	106.9	7647	2527.9
Tax on intermediate consumption																								
Coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Petroleum Products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0	0	33.1	1325.3	26.1	936.3	2933.24	650.2	108.3	1240.2	2413.8	487.4	501.4	935	3410.6	0	27147.1	0	0	0	0	0
Agriculture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Forestry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mineral Products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	128.2	0	0	0	0	128.2
Chemical, rubber, Plastic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metal and Metal products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paper products publishing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transport nec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sea Transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air Transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consuming goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Equipment goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dwellings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	15.5	0.00	394.0	8579.5	2273.4	1020.0	50.0	1007.5	2933.24	650.2	108.3	1240.2	2413.8	487.4	501.4	935	3410.6	0	27275.4	0	0	0	0	27275.4
Value Added	43.75	0.00	539.96	2453.96	3137.34	0.00	0.00	0.00	569.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tax on Investment	0	0	0	0	0	26	20.1	0	0	0	0	0	0	0	0	0	0	0	46.1	0	0	0	0	46.1
Tax on Government consumption																								
Tax on factor	0.2	0.8	0.7	0	0	-4604	7	4.6	0	0	0	0	0	0	0	0	0	0	-4590.7	0	0	0	0	-4590.7
Fix Factor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Labor	0	0.4	0.9	2.3	517.7	-2477.9	58.7	141.1	407.6	116.8	202	517.2	6.7	19.8	673.8	1194.6	1011.5	23.8	3182.6	0	0	0	0	3182.6
Capital	613.2	1060.9	4032.8	4118.1	232.1	7386.8	289	7599	4097.3	14586.4	9248.2	6150	2506	6122.2	4606.8	1385563	37035.9	0	3342.0.6	0	0	0	0	3342.0.6
Import	1.5	0.1	48.3	4518	1.5	1.6	15.3	630.3	0.1	4.7	4.3	0	0	0.0	1.0	0.0	0.0	0	2824.4.3.4	0.0	2824.4.3.4	0	0	2824.4.3.4
Import Margins	12.4	0.1	0.1	1.5	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0	0	0	1.0	0.0	0.0	0	2.7	0	0	0	0	2.7
Import Subsidies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Export subsidies	0	0	0	0	0	-1414	0	0	0	0	0	0	0	0	0	0	0	0	-706.7	0	0	0	0	-706.7
Total Ressources	923.6	1412.6	5630.5	50549.7	49549.3	59003.5	3718.6	45022.1	165920.0	58092.2	69450.4	80224.9	12946.2	24620.2	22576.9	523326.0	130472.3	9781.0	2787823.2	0	0	0	0	2787823.2
Check Balance	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000					
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%					
Households																				192655	292052			1227169
Government																						0		605400
Foreign																				9438204	611109	354441.2		343611
Investment																				1.5e+06				
SAVINGS																				282845	-5303	-14281	280346	

Figure 2: An example of a Social Accounting Matrix used in GEMINI-E3

f_a and f_m are respectively some additive and multiplicative coefficients of the radiative forcing. f_a defines the initial inertia of the forcing. f_m is determined by the climate sensitivity for a doubling of the CO_2 concentration in the atmosphere. f_g is the radiative power of the gas g, given in Table 4.

Table 4: Radiative power of greenhouse gases

f_{CO_2}	5.35
f_{CH_4}	0.0360
f_{N_2O}	0.12

Source (IPCC,[18])

The actual temperature is computed from 2000. The constants l_1 and l_2 represent the inertia related to the temperature transfer atmosphere–ocean.

$$T_{t+1} - \frac{l_{2_t}}{2} PT_{t+1} = T_t(1-l_1)_t^n + \frac{l_{2_t}}{2} PT_t \tag{6}$$

5 A new representation for electricity generation

We enhanced the representation of the electricity generation to model in particular especially the expansion of renewables and the Carbon Capture and Sequestration (CCS) technology. The electricity production is now represented by a nested CES function that describes installed capacities in each type of power plants. Figure 3 gives this nesting structure. We distinguish the activity of generation to the other activities (i.e. transmission and distribution) that are supposed to be common to all types of electricity power plants. Theses two activities (transmission and distribution) are described at the top of the nesting structure. Generation activity is supposed done by two inputs : capital (representing power plants) and fuel. In some cases the fuel input is missing (e.g. for renewable). Note that we do not handle labor input for generation activity. We suppose that labor inputs are not too much different between power plants (nuclear, coal, etc) and we do not associate to each type of power plant a specific labor remuneration. Labor remuneration is globalized and described at the top of nesting structure.

We distinguish six types of power plants

- nuclear power plant;
- coal power plant;
- natural gas power plant;
- petroleum power plant;
- hydro power plant;
- other renewable power plant (mainly wind).

5.1 Investment decision

We compute for each type of power plant (w) the price of production (PDE_{wr}) from the dual function of the CES:

$$PDE_{wr} = \lambda_{wr} \cdot \left[\alpha_{wr} \cdot PK_{wr}^{1-\sigma_{wr}} + (1-\alpha_{wr}) \cdot PFUEL_{wr}^{1-\sigma_{wr}}\right]^{\frac{1}{1-\sigma_{wr}}} \tag{7}$$

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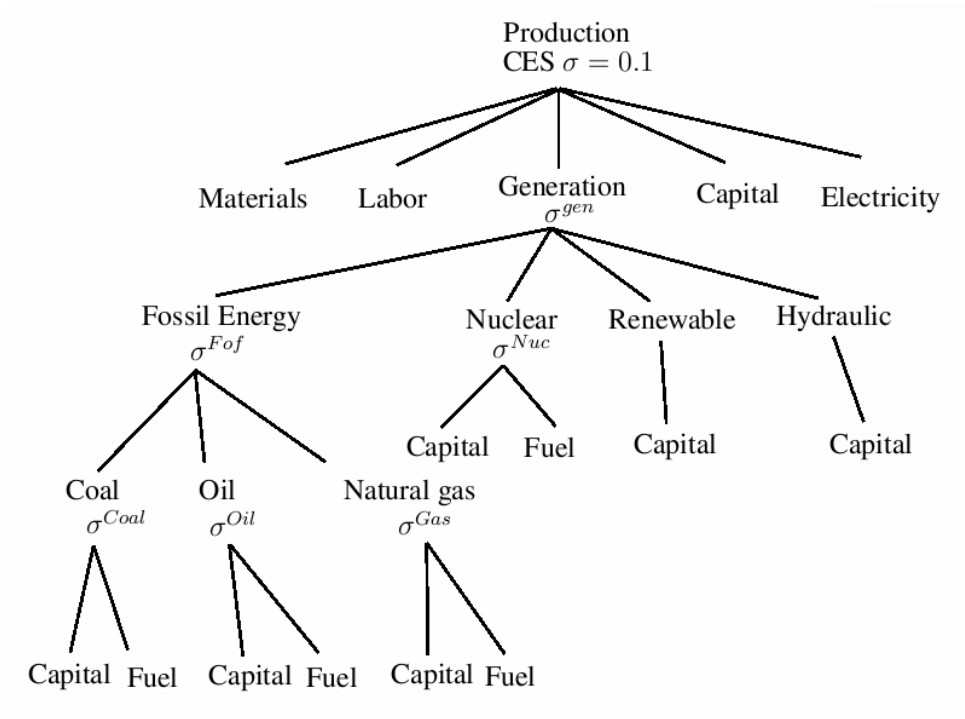

Figure 3: Nesting structure of electricity production

where PK_{wr} is the capital price of power plant w in region r and $PFUEL_{wr}$ is the fuel price. The CES parameters σ_{wr}, α_{wr} and λ_{wr} represent the elasticity of substitution, the share parameter and the technology shifter, respectively.

we can compute demand in the two inputs by the following equations:

$$KE_{wr} = XE_{wr} \cdot \lambda_{wr} \cdot \alpha_{wr} \cdot \left[\frac{PDE_{wr}}{PK_{wr} \cdot \lambda_{wr}}\right]^{\sigma_{wr}} \tag{8}$$

$$FUEL_{wr} = XE_{wr} \cdot \lambda_{wr} \cdot (1 - \alpha_{wr}) \cdot \left[\frac{PDE_{wr}}{PCOMB_{wr} \cdot \lambda_{wr}}\right]^{\sigma_{wr}} \tag{9}$$

where XE_{wr} is the electricity generated by power plant w. For each type of power plant the model described the installed capacity which is equal to investment minus decommissioning. Investment by power plant (IE_{wr}) is determined from an "anticipated" capital demand (KAE_{wr}):

$$IE_{wr} = KAE_{wr} - (1 - \delta_{wr}) \cdot KE_{wr} \tag{10}$$

where δ_{wr} is the capital decay rate. The anticipated capital (KAE_{wr}) is equal to:

$$KAE_{wr} = (1 - \chi_{wr}) \cdot KOE_{wr} + \chi_{wr} \cdot \left(\frac{KE^2_{wr}}{KE^{t-1}_{wr}}\right) \tag{11}$$

where the optimal capital KOE_{wr} is computed through a CES function and anticipated values of prices ($PDEA_{ir}$, $PVAE_{wr}$) and of electricity generation (XEA_{wr}):

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$$KOE_{wr} = XEA_{wr} \cdot \lambda_{wr} \cdot \alpha_{wr} \cdot \left(\frac{\frac{PDEA_{wr}}{PVA_{wr}}}{(R_r + \delta_{wr}) \cdot \lambda_{wr}} \right)^{\sigma_{wr}} \tag{12}$$

with R_r the interest rate.

5.2 Carbon Capture and Sequestration

The model has the possibility to use Carbon Capture and Sequestration (CCS) technology only for coal fired power plant. When the total cost of CCS technology is lower than the carbon price we suppose that all investments in power plants using coal is done with CCS.

6 A new web interface

A new web interface for GEMINI-E3, called GEMINI-E3 web, is available on

http://gemini-e3.ordecsys2.com/.

GEMINI-E3 web is a web application which simulates world climate policies and allows the user to evaluate their impacts at the world level on the climate (emissions and concentrations) and on the economy (GDP, household's surpluses impacts...). The use can simulate two specific world climate policies, a world GHG tax and a GHG emissions reductions. At each user request, GEMINI-E3 web extracts the policy information from a large database containing several hundreds of simulations of GEMINI-E3, then, it compares them with a reference case (also called Business-As-Usual) where no climate policy occurs. Figure 4 displays an example of web results for a simulation of world GHG tax policy defined by a user.

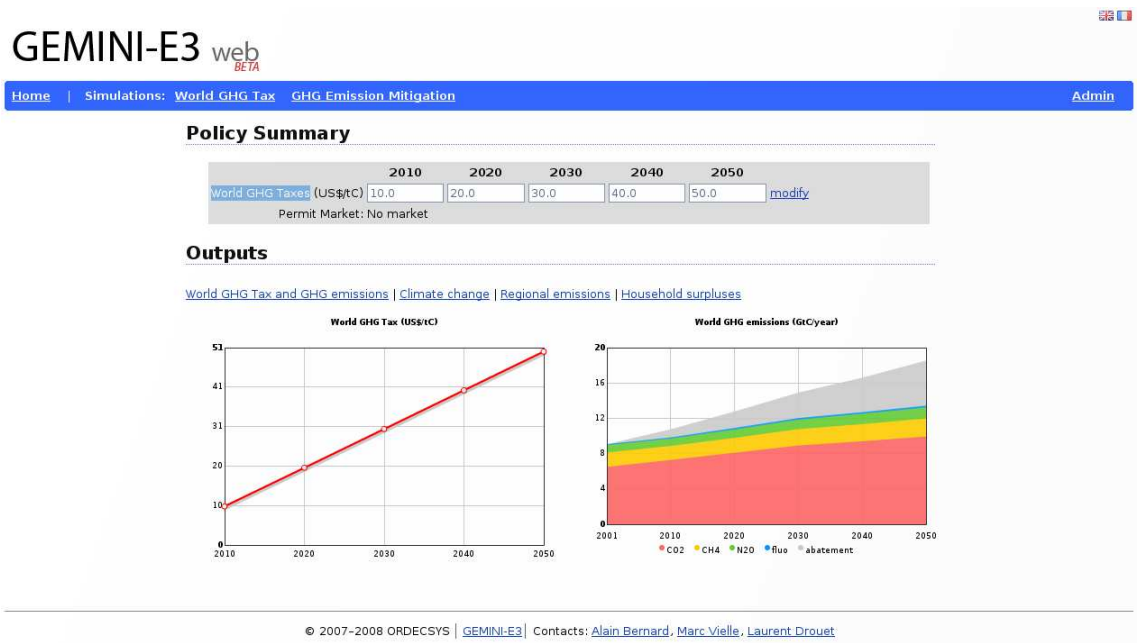

Figure 4: GEMINI-E3 web

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