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GEMINI-E3, a general equilibrium model of international–national interactions between economy, energy and the environment

Alain Bernard · Marc Vielle

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Abstract The purpose of this paper is to present the new version of GEMINI-E3, which is the fifth and incorporates significant changes from the previous version in particular with respect to its size and its modularity. GEMINI-E3 is a Computable General Equilibrium Model and represents now a family of models of different specifications and with several successive versions. It retains many specifications that are common to CGE models but also some specific features, mainly concerning the measurement and analysis of the welfare cost of policies and the great detail in the representation of taxation and social security contributions. The paper gives a detailed presentation of the model, its main blocks and equations, and shows how it can be adapted to specific contexts. In particular a new version is being developed jointly with the standard one, taking into account the constraints of the European Monetary Union and the unbalances in the labor markets of industrialized countries (GEMINI-EMU). This clearly shows that CGE models, beside their main virtue that is total consistency at the domestic and at the world levels, are very flexible in their specification.

1 Introduction

GEMINI-E3 is the name of the first Computable General Equilibrium Model developed jointly by the French Ministry of Equipment and the French Atomic

A. Bernard
Ministry of Equipment, Transport, and Housing, Paris, France
e-mail: alain.bernard@equipement.gouv.fr

M. Vielle (✉)
REME-EPFL, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
e-mail: mvielle@cict.fr

Energy Agency. The team now benefits from a nearly 15 years 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. The new version, which is the fifth, has been developed with the collaboration of the Swiss Federal Institute of Technology (Lausanne). GEMINI-E3 is presently a family of general equilibrium models, all of them multi-sector and dynamic, but some 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 Bernard and Vielle (1998). 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 new types of appraisal, 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. More precisely, the main and successive uses of the model have been directed toward:

- analyzing the implementation of economic instruments for greenhouse gases (GHG) emissions in a second-best setting (Bernard and Vielle 2000b);
- assessing the strategic allocation of greenhouse gases emission allowances in the EU-wide market (Bernard et al. 2005b);
- assessing and comparing regional welfare costs associated with alternative multi-gas strategies for a stabilization of global greenhouse gases emissions in the long run (Bernard et al. 2006);
- analyzing the behavior of Russia in the Kyoto Protocol (Bernard et al. 2003);
- assessing the economic impact of the US withdrawal from the Kyoto Protocol (Bernard and Vielle 2002);
- analyzing the French Climate policy formulated under the Kyoto Protocol (Bernard and Vielle 1999a,b);
- assessing the economic impact of a French nuclear moratorium with respect to the Kyoto Protocol (Bernard and Vielle 2000a);
- assessing the cost of the Kyoto Protocol for Switzerland with and without international emissions trading (Bernard et al. 2005a);
- assessing the double dividend hypothesis of climate change policy, with due consideration to preexisting tax distortions in factor markets for the Swiss economy (Bernard et al. 2004);
- assessing the effects of the increase of oil prices on global and regional GHG emissions (Vielle and Viguier 2007).

A clearer focus put on European climate change policies raised the question of the representation of the European Monetary Union, linking most of the members of the European Union, and of the way of taking into account the constraints of the single currency and the spill-over effects of domestic policies. Effectively, as long as the policies were roughly similar among European

[1] GEMINI-E3 France (Bernard and Vielle 1999a,b), GEMINI-E3 Switzerland (Bernard et al. 2005a), GEMINI-E3 Tunisia (Bernard et al. 2006a).

countries, which means that they also responded in a similar way, there was no need to take explicitly into account the mechanisms of the monetary union. This is not anymore the case when purely domestic policies or significantly differing policies are contemplated. This is the reason why a new version of the model, GEMINI-EMU, has been developed along these lines. The two versions have most in common and the following technical description, specific to GEMINI-E3, is also largely valid for GEMINI-EMU. Differences between the two models will be presented in Sect. 5: though they may appear very limited, they have sweeping effects on policy implementation and efficiency.

As for numerical specification and resolution, the present version of GEMINI-E3 (and GEMINI-EMU) is formulated as a mixed complementarity problem using GAMS with the PATH solver (Ferris and Munson 2000; Ferris and Pang 1997).

2 Structure of the model

As most CGE models, GEMINI-E3 simulates all relevant markets, domestic and international, considered as perfectly competitive, which implies that the corresponding prices are flexible: markets for commodities (through relative prices), for labor (through wages), for domestic and international savings (through rates of interest and exchange rates[2]). Time periods are linked in the model through endogenous real rates of interest determined through the balancing of savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses. There is one notable—and usual—exception to this general assumption of perfect competition, which concerns foreign trade. Goods of the same sector produced by the different countries are not supposed to be perfectly competitive. They are considered as economically different goods, more or less substitutable according to an elasticity of substitution known as Armington's (Armington assumption 1969). A high value means a high degree of competition in the world market, a low value a small degree of competition. This assumption is justified by the high level of aggregation in the nomenclature of goods: agricultural production in developed countries has little in common with agricultural production in developing countries, and significant differences also exist among developed countries and among developing countries. It is also inescapable because, without this assumption, the countries would specialize, each in one sector or a very limited number of sectors.[3] This treatment of

[2] The real exchange rate between two countries is the relative price of the numéraires chosen in each country (and usually based on a basket of goods representative of GDP). Technically, exchange rates for all countries/regions are expressed relatively to a reference one, taken here as AFR (rest of Africa).

[3] This is a side-effect of the general assumption of constant returns to scale in production (with the exception of agriculture and fossil fuels).

foreign trade will be detailed further below. Compared to other CGE models, GEMINI-E3 has two main specificities:

- a comprehensive and detailed representation of indirect taxation. Indirect taxation and social contributions rates are differentiated by commodity (taxes on production, on imports), by sector (social contributions, subsidies), by sector × commodity (intermediate consumption), by commodity × institutional sector (final demand), and by commodity × sector × IS (investment);
- the focus put on the measurement of the welfare cost of policies, and its analysis by main components, either domestic or international ("imported"). Methodology of welfare measurement will be detailed in Sect. 4.

Time periods are linked in the model through endogenous real rates of interest determined by equilibrium between savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses.

Table 1 gives an overall description and the main characteristics of the model. The main outputs of the GEMINI-E3 model are by country and annually: carbon taxes, marginal abatement costs and prices of tradable permits (when relevant), effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms of trade, pure deadweight loss of taxation, net purchases of tradable permits when relevant), macro-economic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and data at the industry-level (e.g. change in production and in factors of production, prices of goods).

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.

2.1 Total demand

For each sector the model computes total demand (Y_{ir}) as the sum of final demand (investment (IV_{ir}), consumption (HC_{ir} and GC_{ir}), exports (EX_{ir})) and intermediate consumption by all sectors (IC_{ikr}):

$$Y_{ir} = HC_{ir} + GC_{ir} + EX_{ir} + IV_{ir} + \sum_k IC_{ikr} \tag{1}$$

where i, r, and k stand for sector, region, and product respectively.

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	

2.2 Imports

Imports (M_{ir}) are computed from total demand according to the Armington assumption (1969):

$$M_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot (1 - \alpha^x_{ir}) \cdot \left[\frac{PY_{ir}}{\lambda^x_{ir} \cdot PI_{ir} \cdot \left(1 + \kappa^i_{ir}\right)} \right]^{\sigma^x_{ir}} \tag{2}$$

where σ^x_{ir}, α^x_{ir} and λ^x_{ir} represent the CES parameters, respectively the elasticity of substitution, the share parameter and the technology shifter and PY_{ir} the price of composite good, PI_{ir} the price of import and κ^i_{ir} the duty rate.

Imports are computed by origins (MR_{irh}) with an another CES function:

$$MR_{irh} = M_{ir} \cdot \lambda^i_{ir} \cdot \alpha^i_{irh} \cdot \left[\frac{PI_{ir}}{\lambda^i_{ir} \cdot PX_{ih} \cdot (e_h/e_r)} \right]^{\sigma^{ai}_{ir}} \tag{3}$$

where e_h is the exchange rate and PX_{ih} the price of exports.

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	1,938	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	1,274.0	1,278	1,293	21.0	13.1	4.1
IND	1,021.1	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	6,071.0	9,742	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

2.3 Domestic production

Figure 1 represents the structure of the production sector in the model. Production technologies are described through nested CES functions. At this stage, we distinguish three different types of representation depending on the characteristics of the sector: sectors including a fixed factor, industry of refined petroleum, other sectors.

2.3.1 Sectors including a fixed factor

Sectors including a fixed factor are the coal, crude oil and natural gas industries. The fixed factor represents the non renewable resources associated with each fossil fuel energy. For these sectors we suppose that the domestic production

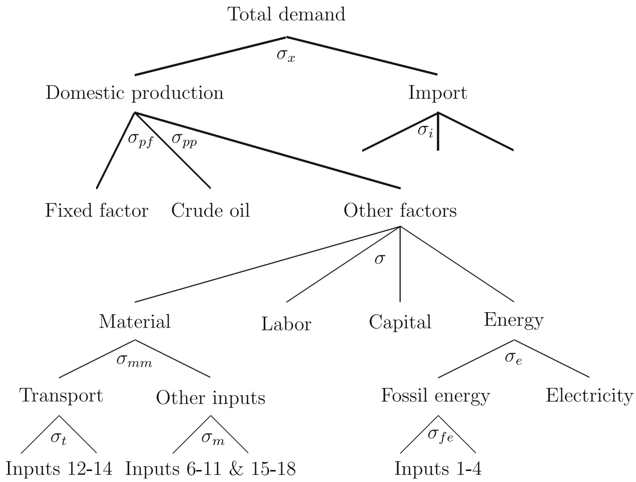

Fig. 1 Structure of the production sector in GEMINI-E3

is realized with this fixed factor and the other standard inputs through a CES function. This specification allows us to take into account the existing resources and its dynamics and the low substitutability between these resources and other inputs. Domestic production (XPF_{ir}) is thus computed through the formula:

$$XPF_{ir} = Y_{ir} \cdot \lambda_{ir}^{x} \cdot \alpha_{ir}^{x} \cdot \left[\frac{PY_{ir}}{\lambda_{ir}^{x} \cdot PDF_{ir}}\right]^{\sigma_{ir}^{x}} \quad \forall i = 1,2,3 \tag{4}$$

and is decomposed between fixed factor (FF_{ir}) and standard inputs consumption (X_{ir}) through a CES function:

$$FF_{ir} = XPF_{ir} \cdot \lambda_{ir}^{pf} \cdot (1 - \alpha_{ir}^{pf}) \cdot \left[\frac{PDF_{ir}}{\lambda_{ir}^{pf} \cdot PF_{ir}}\right]^{\sigma_{ir}^{pf}} \quad \forall i = 1,2,3 \tag{5}$$

and (X_{ir}) is equal to

$$X_{ir} = XPF_{ir} \cdot \lambda_{ir}^{pf} \cdot \alpha_{ir}^{pf} \cdot \left[\frac{PDF_{ir}}{\lambda_{ir}^{pf} \cdot PD_{ir}}\right]^{\sigma_{ir}^{pf}} \quad \forall i = 1,2,3 \tag{6}$$

where PDF_{ir} is the price of domestic production for sectors 1,2,3, PF_{ir} is the price of the fixed factor and PD_{ir} the price of other inputs (i.e standard inputs).

2.3.2 Refined petroleum industry

Refined petroleum products are produced from the basic input, that is crude oil. The model takes into account this specificity with a CES function between crude oil and other inputs at the top level of the nested CES structure. Domestic production of petroleum products (XPP_{4r}) is then equal to:

$$XPP_{4r} = Y_{4r} \cdot \lambda^x_{4r} \cdot \alpha^x_{4r} \cdot \left[\frac{PY_{4r}}{\lambda^x_{4r} \cdot PDP_{4r}} \right]^{\sigma^x_{4r}} \tag{7}$$

crude oil used by refined petroleum sector (IC_{24r}) equal to:

$$IC_{24r} = XPP_{4r} \cdot \lambda^{pp}_{4r} \cdot (1 - \alpha^{pp}_{4r}) \cdot \left[\frac{PDP_{4r}}{\lambda^{pp}_{4r} \cdot PIC_{24r}} \right]^{\sigma^{pp}_{4r}} \tag{8}$$

and standard inputs consumption (X_{4r}) equal to

$$X_{4r} = XPP_{4r} \cdot \lambda^{pp}_{4r} \cdot \alpha^{pp}_{4r} \cdot \left[\frac{PDP_{4r}}{\lambda^{pp}_{4r} \cdot PD_{4r}} \right]^{\sigma^{pp}_{4r}} \tag{9}$$

where PDP_{4r} is the price of domestic production for refined petroleum products, PIC_{24r} is the price of crude oil and PD_{4r} the price of other inputs (i.e standard inputs).

2.3.3 Other sectors

For the other sectors domestic production (X_{ir}) is equal to

$$X_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot \alpha^x_{ir} \cdot \left[\frac{PY_{ir}}{\lambda^x_{ir} \cdot PD_{ir}} \right]^{\sigma^x_{ir}} \quad \forall i = 5, \ldots, 18 \tag{10}$$

where PD_{ir} is the price of domestic production.

2.4 Aggregated inputs

X_{ir} is realized with four aggregated inputs: capital (K_{ir}), labor (L_{ir}), energy (E_{ir}), and material (MA_{ir}). Demand for these factors are then equal to:

$$K_{ir} \cdot \theta^{k\,t}_{ir} = X_{ir} \cdot \lambda_{ir} \cdot \alpha^k_{ir} \cdot \left[\frac{PD_{ir}}{PK_{ir} \cdot \lambda_{ir} \cdot \theta^{k\,-t}_{ir}} \right]^{\sigma_{ir}} \tag{11}$$

$$L_{ir} \cdot \theta^{l\,t}_{ir} = X_{ir} \cdot \lambda_{ir} \cdot \alpha^l_{ir} \cdot \left[\frac{PD_{ir}}{PL_{ir} \cdot \lambda_{ir} \cdot \theta^{l\,-t}_{ir}} \right]^{\sigma_{ir}} \tag{12}$$

$$E_{ir} \cdot \theta^{e\,t}_{ir} = X_{ir} \cdot \lambda_{ir} \cdot \alpha^e_{ir} \cdot \left[\frac{PD_{ir}}{PE_{ir} \cdot \lambda_{ir} \cdot \theta^{e\,-t}_{ir}} \right]^{\sigma_{ir}} \tag{13}$$

$$MA_{ir} \cdot \theta_{ir}^{mt} = X_{ir} \cdot \lambda_{ir} \cdot (1 - \alpha_{ir}^{k} - \alpha_{ir}^{l} - \alpha_{ir}^{e}) \cdot \left[\frac{PD_{ir}}{PM_{ir} \cdot \lambda_{ir} \cdot \theta_{ir}^{m-t}} \right]^{\sigma_{ir}} \tag{14}$$

where θ_{ir}^{k}, θ_{ir}^{l}, θ_{ir}^{e} and θ_{ir}^{m} represent the technical progress incorporated respectively in capital, labor, energy and material.

2.5 Energy consumption by sector

Demand for energy (E_{ir}) is allocated between aggregate fossil fuel consumption (EF_{ir}) and electricity (IC_{5ir}):

$$EF_{ir} = E_{ir} \cdot \lambda_{ir}^{e} \cdot \alpha_{ir}^{ee} \cdot \left[\frac{PE_{ir}}{\lambda_{ir}^{e} \cdot PEF_{ir}} \right]^{\sigma_{ir}^{e}} \tag{15}$$

$$IC_{5ir} = E_{ir} \cdot \lambda_{ir}^{e} \cdot (1 - \alpha_{ir}^{ee}) \cdot \left[\frac{PE_{ir}}{\lambda_{ir}^{e} \cdot PIC_{5ir}} \right]^{\sigma_{ir}^{e}} \tag{16}$$

and demand for each fuel through another CES function:

$$IC_{kir} = EF_{ir} \cdot \lambda_{ir}^{ef} \cdot \alpha_{kir}^{ef} \cdot \left[\frac{PEF_{ir}}{\lambda_{ir}^{ef} \cdot PIC_{kir}} \right]^{\sigma_{ir}^{ef}} \quad \forall k = 1, 3, 4 \tag{17}$$

2.6 Material consumption by sector

Material consumption is allocated between two sub-aggregates, transport services (TR_{ir}) and other material inputs (OTR_{ir}):

$$TR_{ir} = MA_{ir} \cdot \lambda_{ir}^{mm} \cdot \alpha_{ir}^{mm} \cdot \left[\frac{PM_{ir}}{\lambda_{ir}^{mm} \cdot PTR_{ir}} \right]^{\sigma_{ir}^{mm}} \tag{18}$$

$$OTR_{ir} = MA_{ir} \cdot \lambda_{ir}^{mm} \cdot (1 - \alpha_{ir}^{mm}) \cdot \left[\frac{PM_{ir}}{\lambda_{ir}^{mm} \cdot POTR_{ir}} \right]^{\sigma_{ir}^{mm}} \tag{19}$$

which are then allocated between products according to two CES functions:

$$IC_{kir} = TR_{ir} \cdot \lambda_{ir}^{r} \cdot \alpha_{kir}^{r} \cdot \left[\frac{PTR_{ir}}{\lambda_{ir}^{r} \cdot PIC_{kir} \cdot} \right]^{\sigma_{ir}^{r}} \quad \forall k = 12, 13, 14 \tag{20}$$

$$IC_{kir} = OTR_{ir} \cdot \lambda_{ir}^{m} \cdot \alpha_{kir}^{m} \cdot \left[\frac{POTR_{ir}}{\lambda_{ir}^{m} \cdot PIC_{kir} \cdot} \right]^{\sigma_{ir}^{m}} \quad \forall k = 6 \ldots 11, 15 \ldots 18 \tag{21}$$

2.7 Final demand

2.7.1 Households behavior

Household's behavior consists in three interdependent decisions: (1) labor supply; (2) savings; and (3) consumption of the various goods and services. In GEMINI-E3, we suppose that both labor supply and the rate of savings are exogenous. Demand in the different commodities has prices of consumption and income (more precisely "spent" income, income after savings) as arguments and is derived from an utility function whose specifications, as in most CGE models, are a Stone–Geary (1983) or linear expenditure system (LES):

$$u_r = \sum_i \beta_{ir} \cdot ln(HC_{ir} - \phi_{ir}) \tag{22}$$

where ϕ_{ir} represents the minimum necessary purchase of good i, and β_{ir} corresponds to the marginal budget share of good i.

Maximization under budget constraint where HCT_r represents the total expenditure for households consumption, and where PC_{ir} is the price of consumption, gives the demand function:

$$HC_{ir} = \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k (PC_{kr} \cdot \phi_{kr}) \right] \tag{23}$$

2.7.2 Government consumption

Total government consumption (GCT_r) is exogenous and its evolution over time, determined in the calibration of the model, is driven by the growth rates of the main aggregates of the economy. The model splits total consumption between goods (GC_{ir}) on the basis of budget shares β^g_{ir}:

$$GC_{ir} = \beta^g_{ir} \cdot GCT_r \tag{24}$$

2.7.3 Investment

Investment by product (IV_{ir}) is derived from investment by sector (I_{kr}) through a transfer matrix Φ_{ikr}:

$$IV_{ir} = \sum_k \Phi_{ikr} \cdot I_{kr} \tag{25}$$

2.7.4 Exports

In GEMINI-E3 as in any world CGE model, there is no function of exports. For each country/region and each good, the exports (EX_{ir}) are the sum of demands by all other countries/regions that are endogenously determined in the model:

$$EX_{ir} = \sum_h MR_{irh} \tag{26}$$

2.8 The price system

The relations determining the prices of composite goods (PY_{ir}), of domestic production (PD_{ir}, PDF_{ir}, PDP_{ir}), of energy (PE_{ir}), of fossil fuel (PEF_{ir}), of material (PM_{ir}), of transport services (PTR_{ir}) and of other material inputs ($POTR_{ir}$) are derived from the production function, through its nested CES architecture:

$$PY_{ir} = \lambda_{ir}^{x} \cdot \Big[\alpha_{ir}^{x} \cdot PD_{ir}^{1-\sigma_{ir}^{x}} + (1-\alpha_{ir}^{x}) \cdot \big(PI_{ir} \cdot \big(1+\kappa_{ir}^{i}\big)\big)^{1-\sigma_{ir}^{x}}\Big]^{\frac{1}{1-\sigma_{ir}^{x}}} \quad \forall i = 5, \ldots, 18 \tag{27}$$

$$PY_{ir} = \lambda_{ir}^{x} \cdot \Big[\alpha_{ir}^{x} \cdot PDF_{ir}^{1-\sigma_{ir}^{x}} + (1-\alpha_{ir}^{x}) \cdot \big(PI_{ir} \cdot \big(1+\kappa_{ir}^{i}\big)\big)^{1-\sigma_{ir}^{x}}\Big]^{\frac{1}{1-\sigma_{ir}^{x}}} \quad \forall i = 1, 2, 3 \tag{28}$$

$$PY_{ir} = \lambda_{ir}^{x} \cdot \Big[\alpha_{ir}^{x} \cdot PDP_{ir}^{1-\sigma_{ir}^{x}} + (1-\alpha_{ir}^{x}) \cdot \big(PI_{ir} \cdot \big(1+\kappa_{ir}^{i}\big)\big)^{1-\sigma_{ir}^{x}}\Big]^{\frac{1}{1-\sigma_{ir}^{x}}} \quad \forall i = 4 \tag{29}$$

$$PDF_{ir} = \lambda_{ir}^{pf} \cdot \left[\alpha_{ir}^{pf} \cdot PD_{ir}^{1-\sigma_{ir}^{pf}} + (1-\alpha_{ir}^{pf}) \cdot PF_{ir}^{1-\sigma_{ir}^{pf}}\right]^{\frac{1}{1-\sigma_{ir}^{pf}}} \quad \forall i = 1, 2, 3 \tag{30}$$

$$PDP_{ir} = \lambda_{ir}^{pp} \cdot \left[\alpha_{ir}^{pp} \cdot PD_{ir}^{1-\sigma_{ir}^{pp}} + (1-\alpha_{ir}^{pp}) \cdot PIC_{24r}^{1-\sigma_{ir}^{pp}}\right]^{\frac{1}{1-\sigma_{ir}^{pp}}} \quad \forall i = 4 \tag{31}$$

$$PD_{ir} = \lambda_{ir} \cdot \left[\alpha_{ir}^{k} \cdot \left(\frac{PK_{ir}}{\theta_{ir}^{k\,t}}\right)^{1-\sigma_{ir}} + \alpha_{ir}^{l} \cdot \left(\frac{PL_{ir}}{\theta_{ir}^{l\,t}}\right)^{1-\sigma_{ir}} + \alpha_{ir}^{e} \cdot \left(\frac{PE_{ir}}{\theta_{ir}^{e\,t}}\right)^{1-\sigma_{ir}} + (1-\alpha_{ir}^{k}-\alpha_{ir}^{l}-\alpha_{ir}^{e}) \cdot \left(\frac{PM_{ir}}{\theta_{ir}^{m\,t}}\right)^{1-\sigma_{ir}}\right]^{\frac{1}{1-\sigma_{ir}}} \tag{32}$$

$$PE_{ir} = \lambda_{ir}^{e} \cdot \left[\alpha_{ir}^{ee} \cdot PEF_{ir}^{1-\sigma_{ir}^{e}} + (1-\alpha_{ir}^{ee}) \cdot PIC_{5ir}^{1-\sigma_{ir}^{e}}\right]^{\frac{1}{1-\sigma_{ir}^{e}}} \tag{33}$$

$$EF_{ir} = \lambda_{ir}^{ef} \cdot \left[\sum_{k=1,3,4} \alpha_{kir}^{ef} \cdot PIC_{kir}^{1-\sigma_{ir}^{ef}}\right]^{\frac{1}{1-\sigma_{ir}^{ef}}} \tag{34}$$

$$PM_{ir} = \lambda_{ir}^{mm} \cdot \left[\alpha_{ir}^{mm} \cdot PTR_{ir}^{1-\sigma_{ir}^{mm}} + (1-\alpha_{ir}^{mm}) \cdot POTR_{ir}^{1-\sigma_{ir}^{mm}}\right]^{\frac{1}{1-\sigma_{ir}^{mm}}} \tag{35}$$

$$PTR_{ir} = \lambda^{r}_{ir} \cdot \left[\sum_{k=12,13,14} \alpha^{r}_{kir} \cdot PIC^{1-\sigma^{r}_{ir}}_{kih} \right]^{\frac{1}{1-\sigma^{r}_{ir}}} \tag{36}$$

$$POTR_{ir} = \lambda^{m}_{ir} \cdot \left[\sum_{k=6..11,15..18} \alpha^{m}_{kir} \cdot PIC^{1-\sigma^{m}_{ir}}_{kih} \right]^{\frac{1}{1-\sigma^{m}_{ir}}} \tag{37}$$

The equations for base price (PB_{ir}) including tax on production, price of consumption (PC_{ir}), government consumption (PG_{ir}), intermediate consumption (PIC_{ir}), investment (PV_{ir}), labor (PL_{ir}), exports (PX_{ir}), and imports (PI_{ir}) are then:

$$PB_{ir} = \frac{PY_{ir}}{\left(1 - \kappa^{b}_{ir}\right)} \tag{38}$$

$$PC_{ir} = \left(PB_{i} + \kappa^{e}_{ir}\right) \cdot \left(1 + \kappa^{h}_{ir}\right) + \tau^{h}_{ir} \cdot TCO2_{r} \tag{39}$$

$$PG_{ir} = PB_{ir} \cdot \left(1 + \kappa^{g}_{ir}\right) + \tau^{g}_{ir} \cdot TCO2_{r} \tag{40}$$

$$PIC_{ikr} = PB_{ir} \cdot \left(1 + \kappa^{i}_{ikr}\right) + \tau^{i}_{ikr} \cdot TCO2_{r} \tag{41}$$

$$PV_{ir} = \sum_{k} \left(PB_{kr} \cdot \Phi_{kir} \cdot \left(1 + \kappa^{v}_{kir}\right)\right) \tag{42}$$

$$PL_{ir} = W_{r} \cdot \left(1 + \kappa^{w}_{ir}\right) \tag{43}$$

$$PX_{ir} = PB_{ir} \cdot \left(1 + \kappa^{x}_{ir}\right) \tag{44}$$

$$PI_{ir} = \lambda^{i}_{ir} \cdot \left[\sum_{h} \alpha^{i}_{ihr} \cdot \left[PX_{ih} \cdot (e_{h}/e_{r})\right]^{1-\sigma^{ai}_{ir}} \right]^{\frac{1}{1-\sigma^{ai}_{ir}}} \tag{45}$$

where κ^{b}_{ir} is the tax rate on production, κ^{h}_{ir}, κ^{g}_{ir}, κ^{i}_{ikr}, κ^{v}_{ir} are Value Added Tax rates[4] respectively on household consumption, government consumption, intermediate consumption and investment, κ^{e}_{ir} represents the excises (mainly on motor fuel), κ^{w}_{ir} is tax linked to wages (mainly social contribution), κ^{i}_{ir} import duties rate and κ^{x}_{ir} export subsidies rate. τ^{h}_{ir}, τ^{g}_{ir}, τ^{i}_{ikr} are the carbon content of one unit of respectively household consumption, government consumption and intermediate consumption and $TCO2_{r}$ is the carbon tax.

2.9 Capital accumulation

The stock of capital by sector (KC_{ir}) is determined by the classical accumulation formula, with gross investment as input and physical depreciation as output:

[4] Or tax on sales with different tax rates depending on fiscal system of the regions.

$$KC_{ir} = (1 - \delta_{ir}) \cdot KC_{ir}^{t-1} + I_{ir}^{t-1} \tag{46}$$

where δ_{ir} is the rate of capital decay, investment by sector is determined from an "anticipated" capital demand:

$$I_{ir} = KA_{ir} - (1 - \delta_{ir}) \cdot KC_{ir} \tag{47}$$

where the anticipated capital (KA_{ir}) is equal to:

$$KA_{ir} = (1 - \chi_{ir}) \cdot KO_{ir} + \chi_{ir} \cdot \left(\frac{KC_{ir}^2}{KC_{ir}^{t-1}} \right) \tag{48}$$

and where KO_{ir} the optimal capital is computed through a CES function and anticipated values of prices (PDA_{ir}, PVA_{ir}) and of domestic production (XA_{ir}):

$$KO_{ir} \cdot \theta_{ir}^{k\,t+1} = XA_{ir} \cdot \lambda_{ir} \cdot \alpha_{ir}^{k} \cdot \left(\frac{PDA_{ir}}{PVA_{ir} \cdot \frac{R_r + \delta_{ir}}{1 + \kappa_{ir}^{k}} \cdot \theta_{ir}^{k\,-t-1}} \right)^{\sigma_{ir}} \tag{49}$$

with R_r the interest rate and κ_{ir}^{k} is the tax rate on capital income.

The demand for capital is computed through a CES function (see Eq. 11). The demand for capital (K_{ir}) is equal to supply (KC_{ir}) through the rental price of capital (PK_{ir}), see Eq. 56.

2.10 Government budget and Government surplus or deficit

The Government surplus or deficit is the difference between revenues accruing from taxation (direct and indirect, including social security contributions) and expenditures that are of two types: public consumption and transfers to households [mainly social benefits (SB_r)]:

$$\begin{aligned}
SG_r = {} & \sum_i Y_{ir} \cdot \frac{\kappa_{ir}^{b} \cdot PY_{ir}}{(1 - \kappa_{ir}^{b})} + \sum_i PB_{ir} \cdot \kappa_{ir}^{h} \cdot HC_{ir} + \sum_i PB_{ir} \cdot \kappa_{ir}^{g} \cdot GC_{ir} \\
& + \sum_i PI_{ir} \cdot \kappa_{ir}^{i} \cdot M_{ir} + \sum_i PB_{ir} \cdot \kappa_{ir}^{x} \cdot EX_{ir} + \sum_i W_r \cdot \kappa_{ir}^{w} \cdot L_{ir} \\
& + \sum_i PB_{ir} \cdot \sum_k \Phi_{ikr} \cdot \kappa_{kir}^{v} \cdot I_{kr} + \sum_k PB_{kr} \cdot \sum_i IC_{kir} \cdot \kappa_{kir}^{i} \\
& + \sum_i K_{ir} \cdot PK_{ir} \cdot \kappa_{ir}^{k} + \sum_{i=1,4} HC_{ir} \cdot \tau_{ir}^{h} \cdot TCO2_r + \sum_{i=1,4} GC_{ir} \cdot \tau_{ir}^{g} \cdot TCO2_r \\
& + \sum_k \sum_{i=1,4} IC_{ikr} \cdot \tau_{ikr}^{i} \cdot TCO2_r + \kappa_r^{r} \cdot REV_r - \sum_i (GC_{ir} \cdot PG_{ir}) - SB_r
\end{aligned} \tag{50}$$

where κ_r^{r} represents the rate of direct taxation.

2.11 Households budget

Households' savings is determined by the product of income (net of direct taxes and other similar contributions) REV_r and the rate of savings ζ_r:

$$REV_r = W_r \cdot \sum_i L_{ir} + \sum_i K_{ir} \cdot PK_{ir} \cdot (1 - \kappa^k_{ir}) + \sum_i FF_{ir} \cdot PF_{ir} + SB_r \tag{51}$$

$$SH_r = REV_r \cdot (1 - \kappa^r_r) \cdot \zeta_r \tag{52}$$

By difference, one obtains the aggregate households' consumption that is then allocated in the demand for the various commodities.

$$HCT_r = REV_r \cdot (1 - \kappa^r_r) - SH_r \tag{53}$$

2.12 Carbon emissions

Carbon emissions by region are computed from energy consumption by the formula:

$$CO2_r = \sum_{i=1,4} \sum_k IC_{ikr} \cdot \tau^i_{ikr} + \sum_{i=1,4} HC_{ir} \cdot \tau^h_{ikr} + \sum_{i=1,4} GC_{ir} \cdot \tau^g_{ikr} \tag{54}$$

2.13 General equilibrium conditions

The equations below present the clearing market conditions for the various goods, factors of production and balancing conditions between investment and savings on the one hand, imports and exports on the other hand:

$$LS_r = \sum_i L_{ir} \; (R_r) \quad \forall r \tag{55}$$

where LS_r is the supply of labor by households (set exogenously).

$$K_{ir} = KC_{ir} \; (PK_{ir}) \quad \forall i \; \forall r \tag{56}$$

$$FF_{ir} = FS_{ir} \; (PF_{ir}) \quad \forall i = 1, 2, 3 \; \forall r \tag{57}$$

where FS_{ir} is the supply of fixed factor (fixed exogenously).

$$\varepsilon_r = SG_r \; (\kappa^r_r) \quad \forall r \tag{58}$$

It is assumed that in the scenarios the government surplus or deficit remains the same as in the baseline scenario. ε_r.

$$\sum_i M_{ir} \cdot PI_{ir} = \sum_i EX_{ir} \cdot PX_{ir} \; (e_r) \quad \forall r = 1, \ldots, 27 \tag{59}$$

Of course if $n - 1$ trade balances are cleared the trade balance of region 28 is balanced.

$$CO2_r = CO2Q_r \; (TCO2_r) \quad \forall r \tag{60}$$

where $CO2Q_r$ is the constraint for carbon emissions.

General equilibrium relations also include balancing of operations for all agents but, due to the well-known Walras Law, all but one must be taken into account in the resolution of the model. Variables in brackets are those used in the computational algorithm and associated to the corresponding relation.

$$SH_{ir} + SG_{ir} = \sum_i IV_{ir} \cdot PV_{ir} \qquad \forall r \tag{61}$$

2.14 Non carbon greenhouse gas emissions

In the initial version of the model, only carbon dioxide emissions were taken into account. In the present version, and capitalizing from participation to the EMF Working Group 21 (Van Vuuren et al. 2006; Weyant et al. 2006; Scheehle and Kruger 2006; Delhotal et al. 2006; Schaefer et al. 2006; DeAngelo et al. 2006), the model has been updated in order to fully integrate all GHG emissions.[5] For non CO_2 greenhouse gases data on emissions and abatement costs come from the U.S. Environmental Protection Agency (2006). 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 emissions are converted to a CO_2-equivalent basis using the 100-year GWPs defined by the Intergovernmental Panel on Climate Change (Houghton et al. 1997).

U.S. Environmental Protection Agency estimates that world GHG emissions in 2000 were 41 382 millions metric ton of CO_2 equivalents. Figure 2 shows the contribution of non carbon greenhouse gas emissions. They represent 23% of global greenhouse gas emissions, methane accounts for 15%, nitrous oxide for 8% and high global warming potential gases for 1%.

2.14.1 Methane

The model takes into account 13 sources of CH_4 emissions. The emissions of each source are linked to an activity level (or an economic driver) the coefficient of which is calibrated on the baseline scenario:

$$NCO2_{lr} = \frac{\upsilon_{lr}}{{\theta_{lr}}^t} \cdot ED_{lr} \tag{62}$$

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

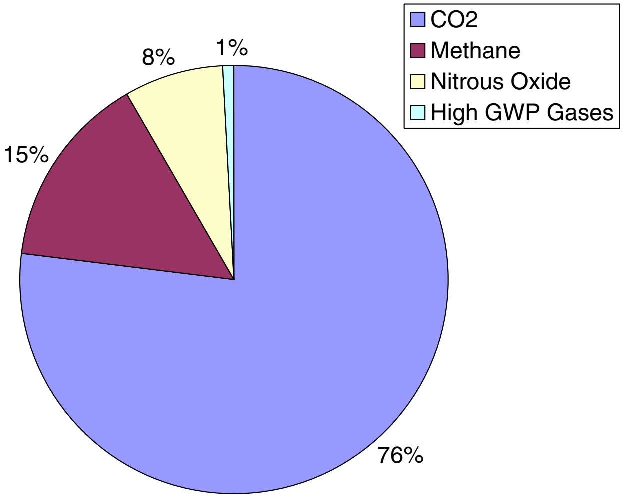

Fig. 2 Breakdown by gas of World GHG emissions (source United States Environmental Protection Agency 2006)

where ED_{lr} is the economic driver, υ_{lr} a coefficient representing the amount of source l emitted by the economic driver and θ_{lr} an exogenous technical progress on the coefficient υ_{lr}.

The Table 3 shows the correspondence between the sources and the sectors/products in GEMINI-E3, the variable of the model representing the economic driver, and whether an abatement curve (MAC) is available for this source.

Table 3 Methane and GEMINI-E3 activities

Source	Index (l)[a]	Economic drivers	MAC
Landfilling of solid waste	LAN	Total household consumption	Yes
Biomass combustion	BIC	Total household consumption	
Fugitives from coal mining activities	COA	Agriculture production	Yes
Enteric fermentation	ENT	Agriculture production	Yes
Stationary and mobile combustion	FUE	Total Demand of refined petroleum	
Other industrial non-agricultural sources	IND	Chemical production	
Oil	OIL	Crude oil production	Yes
Manure management	MAN	Agriculture production	Yes
Rice cultivation	RIC	Agriculture production	Yes
Other agricultural sources	OAG	Agriculture production	Yes
Wastewater	WAS	Total household consumption	
Other non-agricultural sources (waste and other)	OTH	Total household consumption	
Natural gas	GAS	Total demand of natural gas	Yes

[a] For example the index in the case of emissions coming from coal mining is noted $CH4^{Coa}$

Table 4 Nitrous oxide and GEMINI-E3 activities

Source	Index (l)[a]	Economic drivers	MAC
Agricultural Soils	AGS	Agriculture production	
Other agricultural sources	OAG	Agriculture production	
Biomass combustion	BIC	Total household consumption	
Stationary and mobile combustion	FUE	Total demand of refined petroleum	
Manure management	MAN	Agriculture production	
Other non-agricultural sources (waste and other)	OTH	Total household consumption	
Other industrial non-agricultural sources	OIN	Metal and metal goods production	
Adipic acid production	ADI	Chemical production	Yes
Nitric acid production	NIT	Chemical production	Yes
Human sewage	HUM	Total household consumption	

[a] For example the index in the case of emissions coming from adipic acid production is noted $N20^{Adi}$

2.14.2 Nitrous oxide

For N_20 emissions we adopt the same formulation and the Table 4 gives the economic driver for the ten sources of emission.

2.14.3 High global warming potential gases

High global warming potential gas emissions result from the use of substitutes for ozone-depleting substances, from the production of magnesium, aluminum, semiconductors, flat panel display, HCFC-22, electrical equipment and from the use of electrical equipment. GEMINI-E3 distinguishes 11 types of fluorinated gases, they are presented in Table 5.

2.14.4 Curve of abatement

Abatement is computed on the basis of the EMF21 abatement curves (Delhotal et al. 2006; Schaefer et al. 2006; DeAngelo et al. 2006) updated in United States Environmental Protection Agency (2006). In this report marginal abatement cost curves for each region and sector are constructed by estimating the carbon price at which the present value benefits and costs for each mitigation option equilibrate. The methodology produces a stepwise curve, where each point reflects the average price and reduction potential if a mitigation technology were applied across the sector within a given region. These curves have the generic form described in Fig. 3.

We can then compute the level of emissions on the basis of a CO_2 tax:

$$NCO2_{lr} = \frac{\upsilon_{lr}}{{\theta_{lr}}^t} \cdot [1 - f_{lr}(TCO2_r)] \cdot ED_{lr} \tag{63}$$

Table 5 High global warming potential gases and GEMINI-E3 activities

Source	Index (l)	Economic drivers	MAC
ODS substitutes aerosols (Non-MDI)	PFC_AEN	Total household consumption	Yes
ODS substitutes fire Extinguishing	PFC_FIR	Total household consumption	Yes
ODS substitutes foams	PFC_FOA	Total household consumption	Yes
ODS substitutes solvents	PFC_SOL	Total household consumption	Yes
ODS Substitutes aerosols (MDI)	PFC_AEM	Total household consumption	
ODS substitutes refrigeration/ air conditioning	PFC_REF	Total household consumption	Yes
HFC-23 emissions from HCFC-22 production	HFC_22	Total Household consumption	Yes
SF6 emissions from electric power systems	SF6_EPS	Metal and metal goods production	Yes
PFC emissions from primary aluminum production	PFC_PAP	Metal and metal goods production	Yes
HFC, PFC, SF6 from semiconductor manufacturing	PFC_SEM	Equipment goods production	Yes
SF6 emissions from magnesium manufacturing	SF6_MAM	Metal and metal goods production	Yes

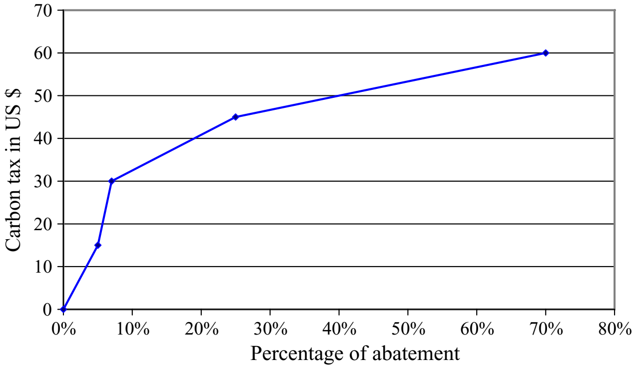

Fig. 3 Curve of marginal abatement costs

where $f_{lr}(TCO2_r)$ is a linear approximation of the abatement curve given by United States Environmental Protection Agency (2006).

2.14.5 Cost of abatement

The cost of abatement is equal to:

$F_{lr}(TCO2_r) \cdot \frac{\upsilon_{lr}}{\theta_{lr}{}^t} \cdot ED_{lr} \cdot f_{lr}(TCO2_r)$ in the case of emissions l , where $F_{lr}(TCO2_r)$ is the integral of the function $f_{lr}{}^{-1}$ in the interval $[0, f_{lr}(TCO2_r)]$.

In order to avoid non-constant returns to scale in production functions, we suppose that the operational cost of abatement is borne by the government and consists in government consumption.

Government consumption is then the sum of two terms (see Eq. 64): a "final" good, which is representative of various services for the economy and in particular for households; an "intermediate" good which is the abatement cost and is equal to $F_{lr}(TCO2_r) \cdot \frac{\upsilon_{lr}}{\theta_{lr}{}^t} \cdot ED_{lr} \cdot f_{lr}(TCO2_r)$.

$$GC_{ir} = \beta^g_{ir} \cdot \left(GCT_r + \frac{\sum_l F_{lr}(TCO2_r) \cdot \frac{\upsilon_{lr}}{\theta_{lr}{}^t} \cdot ED_{lr} \cdot f_{lr}(TCO2_r)}{\sum_i \beta^g_{ir} \cdot PG_{ir}} \right) \tag{64}$$

This distinction is important for GEMINI-E3 because, in order to get relevant yearly measures of welfare cost, we implement the climate change scenarios at constant final demand except, obviously, households' final consumption and imports, and in particular at constant government "final" consumption and constant total investment[6]).

2.14.6 Taxation of non carbon greenhouse gases

Levies on non carbon greenhouse gases are incorporated into the price system: the model computes for all economic drivers the equivalent tax rates on base prices associated to these levies, according to the formula:

$$\kappa^c_{ir} = \frac{TCO2_r \cdot \sum_l \sum_{ED_{lr}(if ED_{lr} \in i)} \frac{\upsilon_{lr}}{\theta_{lr}{}^t} \cdot ED_{lr} \cdot (1 - f_{lr}(TCO2_r))}{Y_{ir} \cdot \frac{PY_{ir}}{1-\kappa^b_{ir}}} \tag{65}$$

We then replace the base price equation (38) by:

$$PB_{ir} = \frac{PY_{ir}}{\left(1 - \kappa^b_{ir}\right)} \cdot \left(1 + \kappa^c_{ir}\right) \tag{66}$$

we must now integrate tax revenues coming from non-carbon greenhouse gas emissions in the government budget and replace Eq. 50 by:

$$\begin{aligned} SG_r = & \sum_i Y_{ir} \cdot \frac{\kappa^b_{ir} \cdot PY_{ir}}{\left(1 - \kappa^b_{ir}\right)} + \sum_i PB_{ir} \cdot \kappa^h_{ir} \cdot HC_{ir} + \sum_i PB_{ir} \cdot \kappa^g_{ir} \cdot GC_{ir} \\ & + \sum_i PI_{ir} \cdot \kappa^i_{ir} \cdot M_{ir} + \sum_i PB_{ir} \cdot \kappa^x_{ir} \cdot EX_{ir} + \sum_i W_r \cdot \kappa^w_{ir} \cdot L_{ir} \\ & + \sum_i PB_{ir} \cdot \sum_k \Phi_{ikr} \cdot \kappa^v_{kir} \cdot I_{kr} + \sum_k PB_{kr} \cdot \sum_i IC_{kir} \cdot \kappa^i_{kir} \\ & + \sum_i K_{ir} \cdot PK_{ir} \cdot \kappa^k_{ir} + \sum_{i=1,4} HC_{ir} \cdot \tau^h_{ir} \cdot TCO2_r + \sum_{i=1,4} GC_{ir} \cdot \tau^g_{ir} \cdot TCO2_r \end{aligned}$$

[6] But of course with an endogenous allocation between sectors.

$$+\sum_{k}\sum_{i=1,4} IC_{ikr}\cdot\tau_{ikr}^{i}\cdot TCO2_r + TCO2_r\cdot\sum_{l} NCO2_{li}$$
$$+\kappa_r^r\cdot REV_r-\sum_{i}(GC_{ir}\cdot PG_{ir})-SB_r$$

finally we modify the equilibrium condition (Eq. 60):

$$CO2_r+\sum_{l} NCO2_{lr}=GHGQ_r\,(TCO2_r)\quad\forall r \tag{67}$$

where $GHGQ_r$ is the constraint on GHG emissions.

3 Calibration and data

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 (Dimaranan 2006), a database that accommodates a consistent representation of energy markets in physical units as well as detailed socio-accounting matrices (SAM) (Reinert and Roland-Holst 1997) for a large set of countries or regions and bilateral trade flows.

The GTAP database is completed by other information especially on indirect taxation and government expenditures, mainly coming from International Energy Agency (International Energy Agency 2002a,b, 2005), OECD (Organisation For Economic Co-operation and Development 2003, 2005) and International Monetary Fund (2004). 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 Fig. 4. Let us recall that the GTAP 6 database is relative to the year 2001 and then that the latter is the base year of the model. Concerning data on population we use the work done by the United Nations (2006).

The default values for elasticity parameters are reported in Table 6.

4 Cost of pollution abatement: measurement and factors

The cost of abatement policies, in their various possible ways of implementation, is a key indicator of the efficiency of climate change policies (Bernard and Vielle 2003). Effectively, when there exists a perfect substitute to the polluting good, or a de-polluting device, the additional cost of the good or of the device measures the welfare cost of abatement. In the case of the greenhouse effect, this is rarely possible, and the bulk of abatement results from the reduction of consumption of GHG emitting goods and their replacement by other factors or less emitting goods, through taxation and changes in relative prices. Measuring welfare cost is then more complex, and in particular macro-economic aggregates such

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	Dwelings	**Total**	Investment	Household Consumption	Government consumption	Export	**Total Uses**
Coal	0.4	0	0	429.5	313.5	0	0	22.9	10.6	12.6	8.1	0	0	0	23.1	7.6	4.2	0	**832.5**	0	96.7	0	0.4	**929.6**
Oil	0	0	0	11412.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**11412.3**	0	0.0	0	0.3	**11412.6**
Gas	0	15.2	35.9	60.2	305.7	41.8	0.2	230.3	599	135.5	178.9	48.3	0.7	1.7	361.8	238.4	1141.1	0	**3394.7**	0	2221.4	0	4.4	**5620.5**
Petroleum Products	0	0	12.9	2401.8	224.4	431.3	8.5	304.6	1836.4	211.5	35.2	4060.4	785.4	1585.9	163.7	72.2	1109.7	0	**13243.9**	0	34656.8	0	2649	**50549.7**
Electricity	108.7	24.7	48.3	236.8	1815	204.7	4.4	800.7	1960.9	2048.1	1011.6	1103.9	15.4	33	1818.3	1858.2	8449.7	0	**21542.4**	0	15405.2	0	3601.6	**40549.2**
Agriculture	0	0	0	1.8	1.8	5105.4	46.1	16.1	165.1	1.5	39.3	19.9	5	8.7	23362.5	366.1	2914.6	1.5	**32055.4**	311.6	17543.6	23	9069.9	**59003.502**
Forestry	0	0	0	0	0.6	7.1	6.2	3.7	31.9	0.6	303.8	0.7	0.1	0.2	204.4	1689	20.2	0	**2268.5**	189	941.3	4.9	315.1	**3718.8044**
Mineral Products	0	0.2	0.6	128.2	135.7	280	1.7	7749.5	2526.4	2812.8	202.7	4.7	1.6	2.1	708.5	7323.2	14482.7	3.6	**36364.2**	57.4	1606.1	2.2	6992.9	**45022.8084**
Chemical, rubber, Plastic	0.1	0.2	0.7	115	190.9	4307.8	25.1	1271.2	35178.6	956.6	1703.3	537.0	86.2	168.5	5023.8	18804.0	12254.6	11.5	**80634.8368**	54.9	34534.6	154.5	50550.2	**165929.056**
Metal and Metal products	0	0.2	0.1	2.9	100.8	141.2	14.9	125.1	674.3	16418.6	23	159.9	1.4	3.1	75.8	22214.2	3836.4	0.9	**43792.8**	94.4	327.3	0.6	13877.1	**58092.2452**
Paper products publishing	0	0	0	5.1	116.7	29.7	1.5	518.1	2500.3	21.8	15455.4	211	54.2	71.2	3136.5	2018	21497	36.9	**45673.4**	14.4	16035.7	7.3	7719.6	**69450.4288**
Transport nec	0.1	1.2	2.4	96.8	482.2	487.2	14.5	2717.5	3701.1	1315.5	4382.8	8275.3	1212.5	2556.8	2527.3	8140	25187.8	8.1	**61109.1**	36	17409.5	420.7	10049.6	**89024.911**
Sea Transport	0	0.3	0.2	3.3	7.8	12	2.1	164.4	9.3	240.9	6.1	606	1406.4	18.5	55.2	81.2	572	0	**3185.7**	1.2	914.4	1.7	8843.2	**12946.2441**
Air Transport	0	0.1	0.2	4	84.7	11.3	1.2	6.6	514.7	14.6	47.2	939.2	9.2	1031.2	98.3	1508.3	6442.2	17.1	**10730.1**	0.4	5035.3	2	8858.4	**24626.2062**
Consuming goods	0.1	0.2	0	2.2	12.8	5695.6	14.7	72.2	3780.4	35.6	566.8	53.1	119.1	112	28868.9	4393.3	14995.2	22.6	**58744.8**	33.7	128394.5	13.1	38550.8	**225736.934**
Equipment goods	0.5	2.8	1.8	104.7	1064.9	1599.1	31.4	1550.8	4096.9	1394.5	1044.5	2387.3	364.4	623.1	4205.1	106449.6	60870.7	61.7	**185853.8**	113257.8	76791.0	665.9	146757.6	**523326.074**
Services	1.6	51.5	9.6	493.7	6473.2	6970.9	242.8	5957.9	22026.8	4683.3	8686.6	8803.7	2551.9	2973	35425.7	76942.3	297919.7	4422.5	**484636.7**	154294.4	301382.9	317157.2	46601.1	**1304072.34**
Dwelings	0	0	0	0	0.1	0.2	0	0.4	0.9	0.1	0.6	0.7	0.1	0.2	0.9	623.6	42	6.2	**676**	0.6	97131.7	3.8	0	**97812.05**
Total	**111.5**	**96.6**	**112.7**	**15498.3**	**11330.8**	**25325.25937**	**415.3165151**	**21511.95422**	**79613.6**	**30304.0514**	**33695.90602**	**27211.05785**	**6613.553341**	**9189.220736**	**106059.7647**	**252729.1592**	**471739.8432**	**4592.550176**	**1096151.14**	**268345.8**	**750428.2**	**318456.9**	**354441.2**	**2787823.21**
Fix Factor	7.8	29.5	21.7	0	0	7495	237	0	0	0	0	0	0	0	0	0	0	0	**7791**					
Social Security	0.46	6.06	4.52	206.49	60.20	5040.41	187.12	2626.94	8428.73	2393.69	4544.97	8678.63	452.69	1309.59	9844.78	32047.87	130624.81	23.43	**206481.402**					
Labor	0.74	9.64	7.18	261.91	73.80	11153.99	414.08	4733.66	14243.97	4342.41	8696.53	14904.07	777.41	2249.01	17686.22	57574.23	225482.09	41.77	**362652.698**					
Capital	0.4	12.6	29.7	79.9	17493.1	7862.04	1986.68	5028.45	15376.71	4026.95	6968.59	17517.04	236.25	681.98	23183.94	41920.84	342849.96	78617.85	**563872.976**					
Value Added	**9.4**	**57.8**	**63.1**	**548.3**	**17627.1**	**31551.44063**	**2824.883485**	**12389.04578**	**38049.4128**	**10763.0486**	**20210.09398**	**41099.74215**	**1466.346659**	**4240.579264**	**50714.93527**	**131542.9408**	**698956.8568**	**78683.04982**	**1140798.08**					
Indirect tax	12.3	35.1	26.7	0	5299	-339.6	-13.1	1505.4	115.4	1078.4	2931.4	40.9	-184.9	-261.4	964.9	-27872.3	44549.6	3379.5	**31267.3**					
Tax on intermediate consumption																								
Coal	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**					
Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24.4	0	**24.4**					
Petroleum Products	0	0	0	0	33.1	1325.3	26.1	936.3	293.824	650.2	108.3	12480.2	2413.8	4874.5	501.4	93.5	3410.6	0	**27147.124**					
Electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	128.2	0	**128.2**					
Agriculture	0	0	0	0	0	-224	0	0	0	0	0	0	0	0	0	0	0	0	**-224**					
Forestry	0	0	0	0	0	-0.4	0	0	0	0	0	0	0	0	0	0	0	0	**-0.4**					
Mineral Products	0	0	0	0	0	-12.4	0	0	0	0	0	0	0	0	0	0	0	0	**-12.4**					
Chemical, rubber, Plastic	0	0	0	0	0	-211.6	0	0	0	0	0	0	0	0	0	0	0	0	**-211.6**					
Metal and Metal products	0	0	0	0	0	-5.7	0	0	0	0	0	0	0	0	0	0	0	0	**-5.7**					
Paper products publishing	0	0	0	0	0	-0.7	0	0	0	0	0	0	0	0	0	0	0	0	**-0.7**					
Transport nec	0	0	0	0	0	-20.3	0	0	0	0	0	0	0	0	0	0	0	0	**-20.3**					
Sea Transport	0	0	0	0	0	-0.6	0	0	0	0	0	0	0	0	0	0	0	0	**-0.6**					
Air Transport	0	0	0	0	0	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	**-0.2**					
Consuming goods	0	0	0	0	0	-203.4	0	0	0	0	0	0	0	0	0	0	0	0	**-203.4**					
Equipment goods	0	0	0	0	0	-70.3	0	0	0	0	0	0	0	0	0	0	0	0	**-70.3**					
Services	0	0	0	0	0	-297.7	0	0	0	0	0	0	0	0	0	0	0.1	0	**-297.6**					
Dwelings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**					
Total	**0**	**0**	**0**	**0**	**33.1**	**278**	**26.1**	**936.3**	**293.824**	**650.2**	**108.3**	**12480.2**	**2413.8**	**4874.5**	**501.4**	**93.5**	**3563.3**	**0**	**26252.524**					
TVA	15.85	0.00	364.04	5679.54	2372.04	1032.60	55.40	263.21	5659.52	53.65	2627.93	1525.81	80.14	441.31	19850.43	12584.47	21891.94	8830.15	**83328.0383**					
Assices	43.75	0.00	529.96	24513.56	3137.36	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	**28224.6324**					
Tax on investment	0	0	0	0	0	26	20.1	0	0	0	0	0	0	0	0	11242.5	16217.4	0	**27506**					
Tax on Government consumption	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**					
Tax on factor																								
Fix 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**					
Labor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**					
Capital	0	0.4	0.9	2.3	517.7	-2477.8	58.7	141.1	407.6	116.8	202	517.2	6.7	19.8	673.8	1194.6	10117.5	2326.8	**13826.1**					
Import	613.2	10605.9	4032.8	4118.1	232.1	7306.8	289	7589	40577.3	14586.4	9248.2	6150	2550.6	6122.2	44506.8	138656.3	37035.9	0	**334220.6**					
Import Margins	123.4	616.1	489.6	159.8	0	836.6	35.3	650.3	1031	478	422.8	0	0	0	1960.4	2586.7	0	0	**9390**					
Import Duties	0	-0.1	-5.68434E-13	29.8	0	209.6	0.1	31.9	181.4	61.7	3.8	0	0	0	1069.8	568.2	0	0	**2156.2**					
Export subsidies	0	0	0	0	0	-141.4	0	0	0	0	0	0	0	0	-565.3	0	0	0	**-706.7**					
Total Ressources	929.60	11412.60	5620.50	50549.70	40549.20	59003.50	3718.80	45022.81	165929.06	58092.25	69450.43	89024.91	12946.24	24626.21	225736.93	523326.07	1304072.34	97812.05	**2787823.21**					
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																						292852		**1227169**
Government																					191655			**605400**
Foreign																								**343611**
Expenditure																					**942084**	**611309**	**354441.2**	
SAVINGS																					285085	-5909	-10831	268346

Fig. 4 Social accounting matrix

Table 6 GEMINI-E3 default parameters

Parameter	Sector	Value	Parameter	Sector	Value
σ	All	0.30	σ_r	All	0.60
σ_{pf}	All	0.20	σ_m	All	0.20
σ_{pp}	All	0.10	σ_x	01,03	2.00
σ_e	01–05	0.10		02	10.00
	06,07,12,13,14	0.20		05	0.50
	Others	0.40		12,13,14,17	0.10
σ_{ef}	01–04	0.10		18	0.05
	05	1.50		Others	3.00
	06–11 and 15–18	0.90	σ_{mm}	All	0.20
	Others	0.30			

as GDP or households' final consumption are not relevant indicators because they are calculated at constant prices, and thus ignore the welfare effects of a change in the structure of prices. The only consistent measure of welfare cost is households' surplus, which can be based either on the compensative variation of income (CVI) or on the equivalent variation of income (EVI). Though theoretically slightly different, they yield very close results as the change in the structure of prices is of a limited magnitude, and energy is a small share in average production cost of the economy and in households' budget. Deriving demand by households from a utility function then allows to have a direct economic measure of the welfare cost of abatement policies. Households' surplus may be directly reckoned from the numerical results of scenarios, for every year and every country/region, and they can be aggregated in various ways: either weighted by exchange rates and summed for a given year or period; or discounted through interest rates for a given country and then measuring the total discounted cost of the abatement policy. For a given period, households' surplus is representative of the total welfare gain if the other elements of final demand (except exports) are held constant. This is the case of the final demand of government, which is exogenous in the model as in most general equilibrium models. Concerning productive investment, which is endogenous in the model and is sensitive to changes in relative prices (and in particular to the change in the relative price of consumption and capital goods), surpluses calculated annually are representative of welfare cost if its total investment[7] is constrained to be constant in the scenario. That is why such a constraint has effectively been retained in the model.

4.1 Measuring surplus

The economic cost of energy and environment policies can be measured comprehensively by changes in households' welfare since final demand of other

[7] But not of course, as noted before, its allocation between sectors.

institutional sectors is supposed unchanged in scenarios. Measurement of this welfare change can be represented by the sum of the change in income and the CVI associated to the change in prices, according to the classical formula. In the case of a Stone–Geary utility function, the compensative variation for a change from an initial situation defined by the price system $(\overline{PC}_{ir})$ to a final situation (PC_{ir}) is such that:

$$\frac{\overline{HCT}_r - \sum_i \overline{PC}_{ir} \cdot \phi_{ir}}{\Pi_i \left(\overline{PC}_{ir}\right)^{\beta_{ir}}} = \frac{\overline{HCT}_r + CVI_r - \sum_i PC_{ir} \cdot \phi_{ir}}{\Pi_i \left(PC_{ir}\right)^{\beta_{ir}}} \tag{68}$$

The households' surplus is then:

$$S_r = \left(HCT_r - \sum_i PC_{ir} \cdot \phi_{ir}\right) - \Pi_i \left(\frac{PC_{ir}}{\overline{PC}_{ir}}\right)^{\beta_{ir}} \left(\overline{HCT}_r - \sum_i \overline{PC}_{ir} \cdot \phi_{ir}\right) \tag{69}$$

4.2 Decomposition of surplus

In a closed economy, households' surplus reflects the pure substitution effect of taxation, i.e. the deadweight loss of taxation (DWL). In an open economy, income effects are added to the pure substitution effect, and they are channeled through the change in the relative prices of foreign trade. Corresponding gains or losses from "terms of trade", as they are known in the specialized literature, may be an important and in some cases a dominant part of the total welfare gain or loss for a given country (though of course, they represent transfers and consolidate at the world level). CVI and Terms of Trade (G_r) can be reckoned directly from the numerical results of the model. DWL is then obtained by subtracting the latter to the former, according to the following "Welfare Cost Algebra":

$$G_r = \sum_i \left(PX_{ir} - \overline{PX}_{ir}\right) \cdot \overline{EX}_{ir} - \sum_i \left(PI_{ir} - \overline{PI}_{ir}\right) \cdot \overline{M}_{ir} \tag{70}$$

$$DWL_r = S_r - G_r \tag{71}$$

4.3 Marginal abatement cost

Definition of the marginal abatement cost may appear obvious, but its precise determination is more complex. According to the theoretical analysis, what is relevant for exchange in a market of tradable permits is the marginal abatement cost defined as the welfare loss at constant prices of foreign trade. On the other hand, this welfare loss is to be deflated by the social value of goods, since the permits is exchanged against tradable goods. Social values of goods differ from market prices of a quantity that is equal to marginal cost of public funds ($MCPF_r$). Calculating marginal abatement cost at constant prices of foreign trade would normally require to operate separately for each country and for each period. However, it is possible to operate globally, and to eliminate the effects of change in the relative price of foreign trade by subtracting to marginal surplus the marginal gain or loss from terms of trade. In other terms, the marginal abatement cost is equal to the marginal deadweight loss of taxation deflated by $MCPF_r$:

$$MAC_r = \frac{1}{MCPF_r} \cdot \frac{\partial DWL_r}{\partial A_r} \tag{72}$$

where A_r represents the abatement in carbon.

As an example, we give the figures obtained for the year 2010 with the previous version of GEMINI-E3 that compares taxes and marginal abatement costs (see Figs. 5, 6). The major result is that for all four countries/regions considered the curve of marginal cost is above the curve of carbon price, with a distance that is relatively more important for France and Japan than for other European countries and the United States. A second observation is that, for high levels of abatement, the relative gap between the two curves tends to decrease. It may happen that the curve of marginal cost be situated below the curve of carbon price, which means in particular that the marginal abatement cost is negative (at least in the first stages of carbon abatement) then exhibiting a "double-dividend" phenomenon. The circumstances leading to a double-dividend are several, and there is in the literature a real competition for producing new cases. Two appear the most important and plausible: energy subsidization; distortions in markets and "rationing" due to price rigidity. Energy subsidization is clearly the situation prevailing in Russia and other ex-FSU countries, and results obtained with the model effectively show that, contrary to other Annex B countries, the curve of MAC is below the curve of carbon price. But as it appears in the Fig. 7, the gap is fairly small, and this may be explained by the low reliability of the statistical system, particularly concerning fiscal data.

5 The new version GEMINI-EMU incorporating the single currency mechanisms

In their vast majority—not to say their totality—world CGE models ignore the existence of monetary unions and in particular the most important one, the

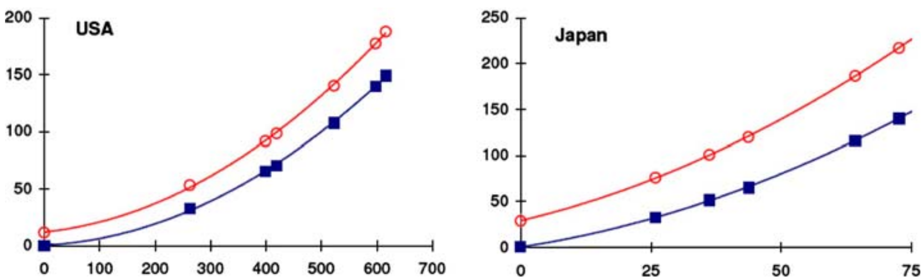

Fig. 5 Marginal abatement cost and tax for USA and Japan (in ECUs 1990 per t of C)

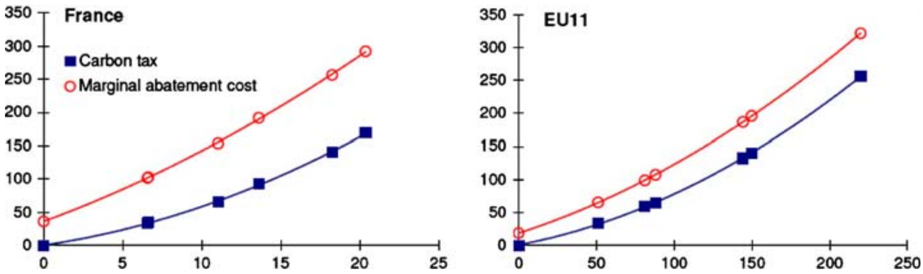

Fig. 6 Marginal abatement cost and tax for France and other European countries (in ECUs 1990 per t of C)

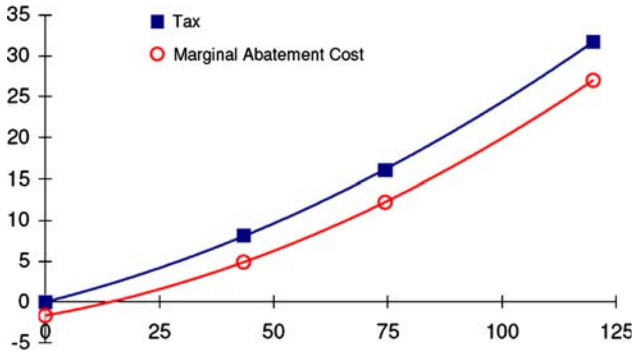

Fig. 7 Marginal abatement cost and tax for Former Soviet Union (in ECUs 1990 per t of C)

European Monetary Union, established by the Maastricht Treaty and operative since January 1999 when the Euro was introduced. It is acknowledged that the existence of a monetary union affects trade, financial markets, macroeconomic policy making and Europe's economic performance and an important and growing literature is devoted to their appraisal, and in particular to the EMU.[8]

Representing the mechanisms and the constraints of a monetary union is not a simple task because by definition they are of "monetary" form and CGE models are essentially in real terms. The challenge is then to formulate—or "translate"—in real terms the monetary mechanisms of the EMU. The most prominent effect of the monetary union and of the use of a single currency across the EMU zone is of course the swing from a system of flexible exchanges rates to a system of fixed exchange rates. This is obvious in monetary terms but has to be transposed in real terms. Changes are also to be considered in the allocation of savings among member countries through the mobility of financial capital. And, at last, the constraints of the Euro become really binding at the macroeconomic level when flexibility in other markets—the labor market in particular—is not warranted.

[8] See for instance (Baldwin et al. 2003; de Grauwe and Melitz 2005); and the numerous working papers in the website of the European Central Bank.

A previous paper in French gives a comprehensive description of the new version of the model, and presents a large set of simulations related to the implementation of a "social VAT" in France (Bernard and Vielle 2006). A following paper in English focuses on similar policies possibly implemented in two other countries belonging to the EMU, Germany and Italy, according to the economic programs of the new Governments in charge and the declarations of their leaders. The presentation below of the structure and characteristics of GEMINI-EMU is taken from this paper.

5.1 Exchange rates

The underlying idea is to select a numéraire, i.e. a basket of goods, representing the Euro currency. More precisely, what is to be formulated is that the price of this numéraire remains constant across the member countries. The real exchange rates between them, calculated with this numéraire, are then fixed.

An obvious candidate for such a numéraire is a "common good" for these countries and it is then to be related to trade between them. The structure of intra-EMU foreign trade varies from one country to the other, and their average—weighted by the share of each country in trade—appears to be a relevant choice, which has been retained.

The exchange rate of the EMU with respect to other countries and regions is still considered as flexible, with the same balancing mechanism as mentioned above, under the constraint that total EMU foreign trade is balanced (or kept to a constant real deficit). Then, with a mechanism ensuring that total EMU foreign deficit is held constant, deficits or surpluses of member countries may diverge and can only be contained through the use of domestic macroeconomic and fiscal policies. But any decrease of deficit in one country has for counterpart an increase in at least one of the other member countries. There is, thus, spill-over effects between member countries channeled through the fixed exchange rates.

5.2 Mobility of capital

But beside stabilizing real exchange rates, the European Monetary Union unifies the money market and correlatively the financial markets. In real terms, this means that savings can be transferred from one country to the other without constraint, according to the expected profitability. In such an assumption of "perfect mobility of capital", equilibrium is reached when profitability is the same, i.e. when real interest rates (and costs of capital for the firms) are also equalized.

Perfect mobility of capital means that *the market for commodities, at the aggregate level, is also unified* with a single balancing constraint between investment and savings. In other terms, any demand for goods (investment goods in particular) that cannot be met in the domestic market is satisfied by imports from other EMU countries. Beside trade based on the above-described mechanism of imperfect competition *a competitive trade but for a single commodity, obviously the Euro-numéraire, must be taken into account*.

The assumption of perfect mobility has also dramatic consequences on EMU-economies, with strong spill-over effects in particular in the case of a decrease of public deficit in a member country. Such a move—resulting either from a tax increase or a decrease of public consumption, leaves room for additional savings but the latter is shared between all member countries. The counterpart is an increase of trade surplus in the considered country and a decrease in other member countries.

Stability of real exchange rates and perfect mobility of capital set up for EMU member countries a totally different economic stage with strong spill-over effects. Efficiency of macroeconomic—and in particular fiscal—policies cannot anymore be assessed with the same standards than in the case of flexible exchange rates and imperfect mobility of capital, which in some way insulates the domestic economy from the world environment, with re-equilibrating and compensating mechanisms through the change in the terms of trade.

Spill-over effects imply that uncoordinated macroeconomic policies in member countries can lead to inefficient equilibria, because no country has an incentive to take them into account. This is not a new idea: as early as in the beginning of the sixties, Richard Mundell warned on the effects of uncoordinated domestic macroeconomic policies within a monetary union and stressed the need for fiscal cooperation, if not harmonization. The various simulations performed with the model, and the results presented in the next section, highlight these two statements.

5.3 Balancing in the labor market

Most—if not all—CGE models assume competitive equilibria in all domestic markets, including the labor market. The reason is that these models, in particular when applied to energy and environment issues, focus on the medium to long run effects, and such an assumption may be considered as likely for such an horizon (at least for developed countries), or at least a standard or a benchmark.

When applied to macroeconomic and fiscal policy, or to sectoral issues on a short to medium run, the representation of the labor market has to be consistent with what is observed, i.e. a persistent unemployment. This is the case of European countries, and particularly member countries of EMU. The main three of them, Germany, France and Italy, have unemployment rates of over or close to 10%. Unemployment has several origins and a comprehensive survey should analyze and measure the importance of each of them. In the framework of a simulation model, we have to consider the one which appears the most important, and the most difficult to alleviate. Beside structural and frictional unemployments, the modern economic theory distinguishes two types, Keynesian and classical (or neo-classical) unemployments.[9]

[9] Another possible cause for unemployment is imperfect competition between firms, whose supply of goods and demand for labor are smaller than in the competitive setting (see Malinvaud 1988).

Keynesian unemployment is the result of unbalance in the markets of goods (at least one of them), due to the stickiness of prices. Classical unemployment is the unbalance in the labor market, due to the stickiness of wages. Formation of wages, obeying to some indexation mechanism rather than the correction of the gap between supply and demand of labor, results in a situation of rationing of the former by the latter. If Keynesian unemployment is likely in a closed economy, it is not credible in an open economy and world markets. Demand for goods is “unlimited”, and what limits the supply by firms is their competitiveness, i.e. the level of output that is profitable at the given market prices. And this is the representation retained in the model.

Under such a representation, an important assumption is linked to the indexation mechanism of wages. Several indexes may be and will be considered in the analysis, the money, the price of GDP and the price of consumption. Monetary indexation means that wages in real money (the numéraire representing the Euro) are held constant. The two other rules index the wages on the numéraires representing the GDP or the households’ final consumption. The latter is the consumer price index, as it can be measured in the model.

It is important to note that, as the model is applied only for simulation purposes, the indexation rules must be understood in “variation”. Over time, and notably in the reference scenario, other mechanisms may or are effectively taken into account. What the above rules mean is that, when a given policy changes the price system, wages are supposed to be increased in the same proportion as the considered index.

Wages indexation plays an important role because it commands the competitiveness of the considered economy. For instance an increase of the VAT has very different effects with an indexation of wages on the CPI than with a nominal indexation (indexation on the GDP price being intermediate).

5.4 A modeling with three numéraires

A special feature of the model is the simultaneous use of three numéraires. The first one is purely “technical”, and is only used to normalize the price system in each country, in each year. Prices of all goods are defined respectively to this numéraire, set equal to one (without loss of generality). Any good can be taken as numééraire, but it is convenient—and usual, particularly in the theory of taxation, to select labor. All prices are then deflated by wages (prices in “purchasing power” of labor). Price systems of each country in each year are connected together through the real exchange rates and the real interest rates.

The second numéraire represents the common currency of the EMU, i. e. the Euro, and is based on the average structure of the intra-EMU trade.

The third numéraire is the reference for wages indexation, either the previous one (nominal indexation) or one of the two price indexes, GDP implicit price or consumer price index (CPI). It can be noted that the selection of labor as “technical” numéraire does not prevent to impose a constraint on wages. Effectively the constraint is on wages deflated by the numéraire of indexation.

As wages are put equal to one, the constraint is effectively on the numéraire of indexation. This is how the model works, but it does not impose any undue constraint on the representation of the economy.

6 Conclusion

Computable General Equilibrium models have a main virtue, which is total consistency both at the domestic and at the world levels, and are then very demanding: any error or approximation is deadly because it is not possible to resolve a square model (same number of variables and equations) if the equations are not compatible.

But—and this is the lesson that can be drawn from our long experience with GEMINI-E3—CGE models are very flexible. First of all in their nomenclatures, with the obvious acknowledgment that a precise assessment of detailed policies may require to increase the number of sectors and/or countries/regions. In our case, we started with three countries/regions and eight sectors and now we are respectively at the figures of 28 and 18.

This is also the case for the specification of the model and the economic mechanisms to be taken into account in order to simulate the effective conditions and working of each economy and the relations between them, through the various channels. Though the initial paradigm of CGE models was full flexibility in all markets, more and more either stickiness or unbalances—in the sense of rationing of demand by supply or vice versa—or institutional constraints—such as the existence of a monetary union—have to be coped with in order to obtain a relevant measure of the effects of contemplated policies. CGE models thus differ significantly from sectoral models because they take into account the indirect effects of policies, through the re-balancing of all markets—whether they are perfectly competitive or not—and the closing of the economic circuit.

These indirect effects are at the heart of what is known—and frequently evoked in the literature—under the term of “double-dividend”. It is of course licit to assert that a given policy—and this is very usual in the case of climate change policies—has a double-dividend but we must explain what are precisely its source and consistence, and check that its sign is effectively positive, not negative.

Acknowledgements Partly supported by TOCSIN (EU-044287).

A Appendix: Variable and parameter dictionary

A.1 Index

i,*k*	:	Sector or product
r,*h*	:	Region
t	:	Time
l	:	Type of non carbon greenhouse gas emissions

A.2 Variables

Quantity

MA_{ir}	:	Material consumption in sector i in region r
MR_{irh}	:	Imports in product i by region r coming from region h
$NCO2_{lr}$	:	non carbon greenhouse gas emissions in source l in region r
OTR_{ir}	:	Other material inputs consumption (i.e. material input minus TR_{ir}) by sector i in region r
TR_{ir}	:	Transport services consumption by sector i in region r
Y_{ir}	:	Total demand in product i in region r
X_{ir}	:	Domestic production for sector i = 5,…, 18, standard inputs consumption for sector i = 1,…, 4
XA_{ir}	:	Anticipated domestic production in sector i in region r
XPF_{ir}	:	Domestic production in fossil fuel product i in region r
XPP_{4r}	:	Domestic production in refined products in region r

Price

e_r	:	Exchange rate of region r
MAC_r	:	Marginal cost of carbon abatement in region r
$MCFP_r$	:	Marginal cost of public funds in region r
PB_{ir}	:	Base price of product i in region r
PC_{ir}	:	Price of household consumption for product i in region r
PD_{ir}	:	Price of domestic production (sector i=5,…, 18) price of standard inputs consumption (sector i=1,…,4)
PDA_{ir}	:	Anticipated price of domestic production in sector i in region r
PDF_{ir}	:	Price of fossil fuel product i in region r
PDP_{4r}	:	Price of petroleum products in region r
PE_{ir}	:	Price of energy in sector i in region r
PEF_{ir}	:	Price of fossil fuel consumption in sector i in region r
PF_{ir}	:	Price of fixed factor in sector i in region r
PG_{ir}	:	Price of government consumption for product i in region r
PI_{ir}	:	Import price of product i in region r
PIC_{kir}	:	Price of intermediate consumption in product k by sector i in region r
PK_{ir}	:	Rental price of capital in sector i in region r
PL_{ir}	:	Labor price in sector i in region r
PM_{ir}	:	Price of material consumption in sector i in region r
$POTR_{ir}$	:	Price of other material inputs (i.e. material input minus TR_{ir}) in sector i in region r
PTR_{ir}	:	Price of transport services inputs in sector i in region r
PV_{ir}	:	Price of investment product i in region r
PVA_{ir}	:	Anticipated price of investment product i in region r
PX_{ir}	:	Export price of product i in region r
PY_{ir}	:	Price of product i in region r
R_r	:	Interest rate in region r
$TCO2_r$	:	Carbon price in region r
W_r	:	Wage in region r

Value

HCT_r : Total consumption in region r
SB_r : Social benefit in region r
SG_r : Government saving in region r
SH_r : Household saving in region r
R_r : Household revenue in region r

A.3 Parameter

Taxation

κ^b_{ir} : Indirect taxes rate of sector i in region r
κ^e_{ir} : Excises tax rate on household consumption of product i in region r
κ^g_{ir} : Tax rate on government consumption of product i in region r
κ^h_{ir} : Tax rate on household consumption of product i in region r
κ^i_{ir} : Duty rate on product i in region r
κ^r_r : Direct tax rate in region r
κ^v_{kir} : Tax rate on investment of product k of sector i in region r
κ^w_{ir} : Tax rate on wages of sector i in region r
κ^k_{ir} : Tax rate on capital income of sector i in region r
κ^x_{ir} : Tax rate on exports of sector i in region r
κ^c_{ir} : Tax rate on base price of sector i in region r due to non carbon greenhouse gas emissions

Coefficient

ϕ_{ir} : Parameter of household consumption: minimum necessary purchase
β_{ir} : Parameter of household consumption: marginal budget share
β^g_{ir} : Share parameter of government consumption
Φ_{ikr} : Transfer matrix between investment by sector and investment by product
τ^h_{ir} : Carbon content of one unit of household consumption in product i
τ^g_{ir} : Carbon content of one unit of government consumption in product i
τ^i_{ikr} : Carbon content of one unit of intermediate consumption in product i by sector k
χ_{ir} : Adjustment factor
ζ_r : Rate of household savings
ε_r : Government saving
λ^x_{ir} : Scale parameter of $CES(M_{ir}$,Domestic production)
λ_{ir} : Scale parameter of $CES(K_{ir}, L_{ir}, E_{ir}, MA_{ir})$
λ^i_{ir} : Scale parameter of $CES(MR_{ir1}, \ldots, MR_{ir28})$
λ^{pf}_{ir} : Scale parameter of $CES(FF_{ir}, X_{ir})$
λ^{pp}_{4r} : Scale parameter of $CES(IC_{24r}, X_{4r})$
λ^e_{ir} : Scale parameter of $CES(IC_{5ir}, EF_{ir})$
λ^{ef}_{ir} : Scale parameter of $CES(IC_{1ir}, IC_{3ir}, IC_{4ir})$
λ^{mm}_{ir} : Scale parameter of $CES(TR_{ir}, OTR_{ir})$

λ_{ir}^{r} : Scale parameter of $CES(IC_{12ir}, IC_{13ir}, IC_{14ir})$
λ_{ir}^{m} : Scale parameter of $CES(IC_{6ir}..IC_{11ir}, IC_{15ir}..IC_{18ir})$
σ_{ir}^{x} : Elasticity parameter of $CES(M_{ir}$,Domestic production)
σ_{ir}^{ai} : Elasticity parameter of $CES(MR_{ir1}, \ldots, MR_{ir28})$
σ_{ir} : Elasticity parameter of $CES(K_{ir}, L_{ir}, E_{ir}, MA_{ir})$
σ_{ir}^{pf} : Elasticity parameter of $CES(FF_{ir}, X_{ir})$
σ_{4r}^{pp} : Elasticity parameter of $CES(IC_{24r}, X_{4r})$
σ_{ir}^{e} : Elasticity parameter of $CES(IC_{5ir}, EF_{ir})$
σ_{ir}^{ef} : Elasticity parameter of $CES(IC_{1ir}, IC_{3ir}, IC_{4ir})$
σ_{ir}^{mm} : Elasticity parameter of $CES(TR_{ir}, OTR_{ir})$
σ_{ir}^{r} : Elasticity parameter of $CES(IC_{12ir}, IC_{13ir}, IC_{14ir})$
σ_{ir}^{m} : Elasticity parameter of $CES(IC_{6ir} \ldots IC_{11ir}, IC_{15ir} \ldots IC_{18ir})$
α_{ir}^{x} : Share parameter of $CES(M_{ir}$,Domestic production)
α_{irh}^{i} : Share parameter of $CES(MR_{ir1}, \ldots, MR_{ir28})$
α_{ir}^{k} : Share parameter for capital in $CES(K_{ir}, L_{ir}, E_{ir}, MA_{ir})$
α_{ir}^{l} : Share parameter for labor in $CES(K_{ir}, L_{ir}, E_{ir}, MA_{ir})$
α_{ir}^{e} : Share parameter for energy in $CES(K_{ir}, L_{ir}, E_{ir}, MA_{ir})$
α_{ir}^{pf} : Share parameter of $CES(FF_{ir}, X_{ir})$
α_{4r}^{pp} : Share parameter of $CES(IC_{24r}, X_{4r})$
α_{ir}^{ee} : Share parameter of $CES(IC_{5ir}, EF_{ir})$
α_{ir}^{ef} : Share parameter of $CES(IC_{1ir}, IC_{3ir}, IC_{4ir})$
α_{ir}^{mm} : Share parameter of $CES(TR_{ir}, OTR_{ir})$
α_{ir}^{r} : Share parameter of $CES(IC_{12ir}, IC_{13ir}, IC_{14ir})$
α_{ir}^{m} : Share parameter of $CES(IC_{6ir} \ldots IC_{11ir}, IC_{15ir} \ldots IC_{18ir})$
υ_{lr} : Emission coefficient linking non carbon greenhouse gas emissions l and its economic driver υ_{r}^{l}
θ_{ir}^{k} : Technical progress on capital
θ_{ir}^{l} : Technical progress on labor
θ_{ir}^{e} : Technical progress on energy
θ_{ir}^{m} : Technical progress on material
θ_{lr} : Technical progress on emission coefficient υ_{r}^{l}
δ_{ir} : Rate of capital decay of sector i in region r

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