A Coupled Bottom-Up / Top-Down Model for GHG Abatement Scenarios in the Swiss Housing Sector *

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Abstract. In this paper we report on the coordinated development of a regional module within a world computable general equilibrium model (CGEM) and of a bottom up energy-technology-environment model (ETEM) describing long term economic and technology choices for Switzerland to mitigate GHG emissions in accordance with Kyoto and post-Kyoto possible targets. We discuss different possible approaches for coupling the two types of models and we detail a scenario built from a combined model where the residential sector is described by the bottom-up model and the rest of the economy by the CGEM.

1. Introduction

This paper reports on the coordinated development of a top-down macro-economic model and a bottom-up technology-energy-environment model to assess long term climate policies in Switzerland. This work is undertaken under the aegis of a Swiss research network[1] concerned by the various dimensions of climate studies. We briefly present (i) a computable general equilibrium model (CGEM) which places Switzerland in a world model called GEMINI-E3 and (ii) a bottom-up energy-technology-environment model (ETEM) inspired from the MARKAL

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[1] The Swiss NSF NCCR-Climate.

modelling framework. We then show how one can couple the two models to obtain a hybrid top-down/bottom-up model producing a macro-economic scenario with detailed technology description for the residential sector in Switzerland.

In the literature the relations between the economy, the energy sector and the environment are described in two broad classes of models called *top-down* and *bottom-up* respectively. The first category approaches the problem from a description of the macro-economic relations in the region under consideration, whereas the bottom-up models propose a technology rich description of the energy system and place the emphasis on the correct description of energy options and their cost structure. These two categories of models are complementary, the former capturing a larger set of economic interactions (i.e. inter-industrial relations and macro-economic feedbacks) without representing explicitly energy technology options and the latter representing well the details of the energy sector and the technology ranking procedures in a world characterized by technological innovation. Bottom-up models are used to compute partial economic equilibria in the energy sector under different constraints on pollutant or GHG emissions. They usually assume perfect foresight and produce optimized technology investment policies over a planning horizon of several decades typically 45 years for MARKAL models. These models are driven by energy service demands that are either exogenously defined or dependent on their own prices supposed to be indicated by the long term marginal cost of demand constraints, with exogenously defined price-elasticities. The optimization over a long time horizon coupled with a rather limited economic feedback induced by changes in relative prices makes these models more "prescriptive" than "predictive" of what could really happen.

On their side, top-down models tend to neglect the description of energy and technology options, in particular the possible introduction of new options. Because they are "technology-poor" they tend to overemphasize the economic adjustments and overlook the possible technology changes that will be induced by the changes in relative prices. Because of this complementarity it appears promising to go beyond this taxonomy of economy-energy-environment models. Already, a number of existing models are "hybrid", providing simultaneously some details on the structure of the economic and technological sectors (Böhringer, 1998; Weyant, 1999). Different approaches have been used: (i) *Coupling optimal growth models with energy system models*: ETA-MACRO and MARKAL-MACRO are examples of a coupling of a bottom-up MARKAL model with an optimal economic growth model à la Ramsey which determines through inter-temporal optimization the optimal path of capital accumulation and demand for energy services, under specified emissions reduction (Manne and Richels, 1992; Manne and Wene, 1992). (ii) *Coupling input-output economic models with energy system models*: In this approach the economy is described by a Leontieff model of interindustry exchange; the energy sector is detailed as a linear production system. (iii) *Coupling a CGEM with an ETEM*: This is the most attractive type of coupling, since a CGEM provides a more complete representation of the different economic feedbacks and permits a correct treatment of the different taxes and market imperfections in the economy under consideration (Schafer and Jacoby, 2003).

The present paper is an attempt to implement the third type of coupling with a focus on the residential sector in the Swiss economy. The paper is organized as follows: in section 2 we briefly recall Swiss climate policy and we show why the focus on the residential sector is justified. In section 3 we describe the GEMINI-E3 implementation for Switzerland. In section 4 we describe the ETEM-SWI development. In section 5 we describe the coupling of GEMINI-E3 and the residential sector in ETEM-SWI. In section 6 the scenarios obtained with the CGEM and the ETEM run in a stand-alone fashion are compared and the gain in insight obtained through the coupling is assessed. Section 7 concludes and proposes further developments.

2. Swiss CO_2 Policy and the Housing Sector

Switzerland ratified the United Nation's Framework Convention on Climate Change (UNFCCC) in 1993 and the Kyoto Protocol in June 2003. In the Protocol, Switzerland's commitment amounts to 8% reduction in its net emissions of six greenhouse gases (GHG) over the period 2008-12, compared to 1990 emissions. This is the same target as for the European Union.

Switzerland does not address climate change with a unique policy, but rather with a combination of measures and policies in various areas. The main spearheads of its strategy are the Federal Law on the reduction of CO_2 emissions ("CO_2 Law") and the Federal Energy Law. The 1999 CO_2 Law sets as an overall target that CO_2 emissions over the period 2008-12 have to be 10% below the 1990 level, with differentiated targets for heating and process fuels (-15%) and motor fuels (-8%). The law provides for a "supplementary" CO_2 tax to be implemented at the earliest in 2004 and the revenues of which are to be fully redistributed to the population and economic sectors.

The 1998 "Energy Law" calls for extensive collaboration with the private sector, mainly within the framework of a public voluntary programme called “SwissEnergy”, which replaces the “Energy 2000” programme that ran from 1990 to 2000. Private energy agencies have been created in order to coordinate, evaluate and monitor voluntary initiatives. The programme mainly focuses on energy efficiency measures, in particular for electrical appliances and vehicles, but also favours the production and use of renewable energy.

This unique combination of voluntary approaches with an emissions trading programme and a CO_2 tax has been analyzed in Baranzini and Thalmann (2004). Here we emphasize the role of housing in energy consumption, CO_2 emissions and efforts to reduce those emissions. Some background information on global energy consumption and CO_2 emissions is nevertheless necessary.

Swiss CO_2 emissions are stabilized since the 1990s, but it is doubtful that they will decline to the targets set in the Kyoto Protocol and CO_2 Law. In 2002, total GHG emissions amounted to 52.3 million tonnes of CO_2 equivalents. CO_2 represents the largest proportion of gross GHG emissions (about 84%). About 80% of total GHG emissions are energy related. Given the Swiss energy consumption profile, that means that the greatest part of GHG emissions stems from the use of fossil fuels. That explains why the CO_2 Law only addresses CO_2 emissions linked to the energetic use of fossil fuels.

Figure 1 shows the main CO_2 sources since 1990 (from Swiss GHG inventory in SAEFL (2000)). The shares are quite stable. Transportation accounts for the largest share, rising slowly from about 32% in the early 1990s to 35% in the early 2000s. The share of emissions from residential energy use was about 27% in the first half of the 1990s and was lowered to about 25% today. In total quantity those emissions were hardly lowered but per capita they went down from 1.82 tonne in 1991 to 1.52 tonne in 2002.

Note the relatively small share of industry-related CO_2 emissions. Indeed, Switzerland imports a very large proportion of intermediate and final goods with high energy content. The emissions associated with the production of those goods are not counted as Switzerland’s contribution to the accumulation of GHGs. They have been estimated at 60 to 70% of domestic emissions. A second and related factor is the near absence of heavy industries and the high share of the services sector in GDP (67% in 1999). A third factor is the near absence of coal- or oil-fired power plants for electricity generation. The first nuclear power plant was hooked to the grid in 1969. Thirty years later, nuclear power plants produce nearly 35% of electric energy. 60% are produced by hydroelectric power plants. The production of thermal power stations has been insignificant throughout the twentieth century. Of course, the high shares of hydropower and nuclear in electricity generation help

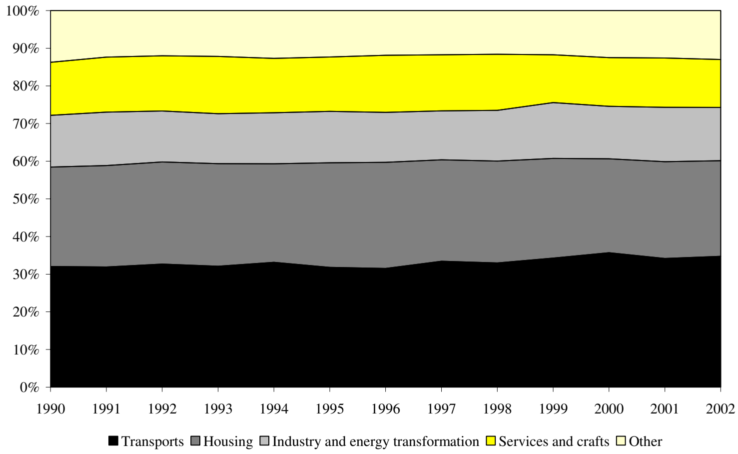

Figure 1. Main sources of CO_2 emissions

keep down CO_2 emissions. However, electricity represents only 22% of total final energy consumption of 855.3 PJ in 2000. The bulk share is that of oil products and they are entirely imported.

The drawback of this good performance is that it will be quite costly to further reduce the CO_2 intensity of the Swiss economy. Even the 8% target set in the Kyoto Protocol would be very demanding if economic growth were not so sluggish. Indeed, it is generally recognized that the marginal abatement cost for Switzerland is among the highest in OECD countries (for example, see Kram and Hill (1996), Bahn et al. (1998), and Bernard et al. (2004b)). On the other hand, Switzerland has additional incentives for reducing its use of fossil energy, namely reducing its imports and its dependency on world oil supply.

In many European countries, heavy industry bore the bulk of CO_2 emissions reductions. That is not possible in Switzerland and therefore the other sectors, most notably transportation and housing, must also contribute their share. Efforts to curb fuel consumption in the transportation sector meet fierce resistance by the oil sector, car owners and their organizations. Better results are obtained in the housing sector.

CO_2 emissions by the housing sector declined from 12.4 Mt in 1991 and 1992 to 11.3 Mt in 2001 and 2002 (Table 2). This was obtained in spite of growing population, a number of dwellings that grows even more and dwellings that get larger and larger.

The reduction in CO_2 emissions was obtained both through a reduction in energy consumption and changes in the energy mix. The latter

Table I. Determinants of energy demand by housing sector and CO_2 emissions

	Mean 1991-92	Mean 2001-02	% change
Population (mio)	6.84	7.26	6.2%
Number of dwellings (mio)	3.19	3.61	13.1%
Mean surface of occupied dwellings (m^2)	93	106	14.0%
Final energy consumption (PJ)	243.3	239.2	-1.7%
CO_2 emissions by housing sector (Mt)	12.4	11.3	-9.0%

Notes: data from Swiss federal energy office and statistical office.
Surface of dwellings is from 1990 and 2000 censuses.

is illustrated in Table 2. Light fuel oil remains the main energy source but natural gas is catching up.

Table II. Energy mix in housing

	1990 (TJ)	% total	2003 (TJ)	% total
Light fuel oil	139170	61.1	129540	52.2
Electricity*	47570	20.9	60040	24.2
Natural gas	25620	11.3	40330	16.2
Biomass	8430	3.7	8500	3.4
Distance heating*	4400	1.9	5220	2.1
Other renewables*	1820	0.8	4500	1.8
Coal	650	0.3	130	0.1

Source: Based on OFEN (2003); Energy bearers marked with a * are not counted in CO_2 emissions of housing sector. Distance heating is generally obtained from incinerating household waste.

Regulation varies from canton to canton. In several cantons, new builders and owners who renovate are required to insulate their buildings and to install individual energy meters in each dwelling. Severe restrictions apply to air conditioning and electric heating. On the other hand, no demands are imposed on older buildings. Heating oil is virtually exempted from the fuel tax that adds about 76 Swiss cents to the liter of diesel, the equivalent motor fuel (diesel).

For older buildings and in the cantons that impose no regulation, the main instruments used to reduce fossil energy consumption by the housing sector are financial incentives and information. Small incentives are provided for the use of renewable energy and better insulation. The "Energy 2000" and "SwissEnergy" programmes provide technical assistance and promote a label for buildings with low energy consumption.

Such incentives are often offset by rent regulation[2]. Indeed, investments to reduce energy consumption cannot be passed on to the tenants who benefit from the lower energy expenses. Nor have the tenants any influence on decisions to renovate or not.

Thus, there remains a large potential for energy savings in the housing sector, a sector that still contributes one fourth of all CO_2 emissions. The technologies are available for improvements at relatively low marginal cost.

3. GEMINI-E3

The GEMINI-E3 is a dynamic-recursive CGE model that represents the world economy in 21 regions (including Switzerland) and 14 sectors. It incorporates a highly detailed representation of indirect taxation (Bernard and Vielle, 1998). GEMINI-E3 is formulated as a Mixed Complementarity Problem (MCP) using GAMS with the PATH solver (Ferris and Pang, 1997; Ferris and Munson, 2000). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-5 database (Hertel, 1997), that expresses a consistent representation of energy markets in physical units as well as a detailed Social Accounting Matrix (SAM) for a large set of countries or regions and bilateral trade flows. It is the fourth GEMINI-E3 version in this succession that has been especially designed to calculate social marginal abatement costs (Bernard and Vielle, 2003) (MAC, i.e. the welfare loss of a unit increase in pollution abatement). The original version of GEMINI-E3 is fully described in Bernard and Vielle (1998)[3]. Updated versions of the model have been used to analyze the implementation of economic instruments for GHG emissions in a second-best setting (Bernard and Vielle, 2000), to assess the strategic allocation of GHG emission allowances in the EU-wide market (Viguier et al., 2004), to analyze the behavior of Russia in the Kyoto Protocol (Bernard et al., 2003; Bernard et al., 2004), and to assess the costs of Kyoto for Switzerland with and without international emissions trading (Bernard et al., 2004b).

[2] Two thirds of Swiss households live in rental dwellings, mostly in multi-family buildings.

[3] for a complete description of the model see our web site and the technical document downloadable at: http://ecolu-info.unige.ch/∼nccrwp4/GEMINI-E3/HomeGEMINI.htm.

Beside a comprehensive description of indirect taxation, the strength of the model is to simulate all relevant markets: e.g. commodities (through relative prices), labor (through wages), and domestic and international savings (through rates of interest and exchange rates). Terms of trade (i.e. transfers of real income between countries resulting from variations of relative prices of imports and exports), and then "real" exchange rates can be accurately modeled.

Time periods are linked in the model through endogenous real rates of interest determined by the 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.

The main outputs from the GEMINI-E3 model are, by country and annually: carbon taxes, marginal abatement cost and price 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), macroeconomic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and industry data (e.g. change in production and factors of production).

For each sector the model computes the total demand (Y_{ir}) that includes household consumption (HC_{ir}), government consumption (GC_{ir}), exports (EX_{ir}), investment (IV_{ir}), and intermediate uses (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 sectors, regions, and products respectively.

Total demand is then divided between domestic production (X_{ir}) and imports (M_{ir}). The model employs a convention that is widely used in modeling international trade: the Armington assumption (Armington, 1969). Under this convention a domestically produced good is treated as a different commodity from an imported good produced in the same industry.

$$X_{ir} = Y_{ir} \cdot \lambda_{ir}^{x} \cdot \alpha_{ir}^{x} \cdot \left[\frac{PY_{ir}}{\lambda_{ir}^{x} \cdot PD_{ir}} \right]^{\sigma_{ir}^{x}} \tag{2}$$

$$M_{ir} = Y_{ir} \cdot \lambda_{ir}^{x} \cdot (1 - \alpha_{ir}^{x}) \cdot \left[\frac{PY_{ir}}{\lambda_{ir}^{x} \cdot PI_{ir} \cdot (1 + \kappa_{ir}^{i})} \right]^{\sigma_{ir}^{x}} \tag{3}$$

where PY_{ir} represent the price of production, PD_{ir} is the price of domestic production, and PI_{ir} is the price of imports; σ_{ir}^{x}, α_{ir}^{x}, λ_{ir}^{x},

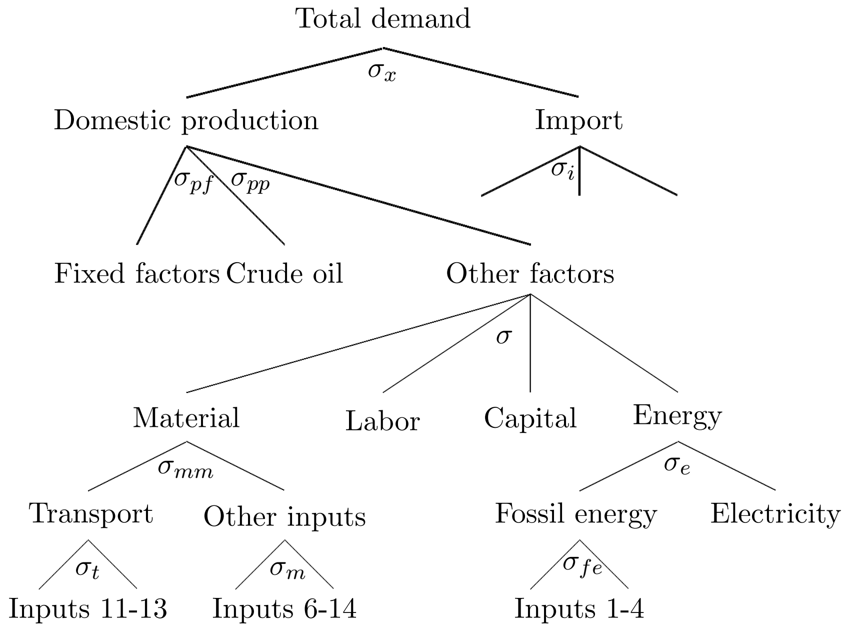

Figure 2. Structure of the Production Sector in GEMINI-E3

and κ_{ir}^i represent the CES parameters, respectively, the elasticity of substitution, the share parameter, the technology shifter, and the duty rates.

Figure 2 represents the structure of the production sector in the model. Production technologies are described using nested CES functions.

Household's behavior consists in three interdependent decisions: 1) labor supply; 2) savings; and 3) consumption of the different goods and services. In GEMINI-E3, we suppose that labor supply and the rate of saving are exogenously set. The utility function is assumed to have a Stone-Geary form (Stone, 1983) which is written as:

$$u_r = \sum_i \beta_{ir} \cdot ln(HC_{ir} - \phi_{ir}) \tag{4}$$

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

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

$$HCT_r = \sum_i PC_{ir} \cdot HC_{ir} \tag{5}$$

yields :

$$HC_{ir} = \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k (PC_{kr} \cdot \phi_{kr}) \right] \tag{6}$$

4. ETEM-Switzerland

ETEM-SWI (Energy-Technology-Environment model for Switzerland) is a linear programming model of the production, trading, transformation, distribution and end-uses of various energy forms in Switzerland. It belongs to the family of the well-known techno-economic MARKAL[4] models, developed under the auspice of the international consortium of Energy Technology Systems Analysis Programme (ETSAP). The current version of ETEM-SWI uses the same structure and analytical tools as the World MARKAL model described in Labriet et al. (2004) and Kanudia et al. (2004). It also belongs to the same family of MARKAL models as the MARKAL model for Switzerland (Bahn et al., 1998) and Geneva (Fragnière and Haurie, 1996a; Fragnière and Haurie, 1996b).

ETEM-SWI computes a supply-demand partial economic equilibrium on Switzerland's energy markets that maximizes net total surplus (i.e. the sum of producers' and consumers' surpluses) over 2000-2050, while satisfying the demands for energy services (demand-driven model) and a number of constraints (e.g. environmental constraint). The model, like most equilibrium models, assumes perfectly competitive energy markets, except in cases where user-defined, explicit special constraints are added (e.g. limits to the penetration of some technologies, see below). Moreover, the model is run in a dynamic manner, assuming perfect information and foresight, so that investment decisions are made with full knowledge of the future.

The total cost of the system includes, at each time period: annualized investments in technologies, fixed and variable annual operation and maintenance costs of technologies; cost of energy imports and domestic resource production; revenue from energy exports; delivery costs; losses incurred from reduced end-use demands; and taxes and subsidies associated with energy sources, technologies, and emissions. The outputs from the model are: investments in technologies, operating levels for each type of technology, in each time period, levels of primary resource

[4] MARKAL (MARKet ALlocation) is a dynamic linear programming model of the energy system and the environment of a given country or region (Fishbone and Abilock, 1981; Berger et al., 1992; Kram and Hill, 1996; Kypreos, 1996; Loulou and Kanudia, 2002).

availability, and levels of energy carrier purchased from and/or sold to other regions. Of course, emissions and energy mix result from all these decisions.

ETEM-SWI is technology rich with more than 1600 technologies. The reference energy system is disaggregated into five energy consumption sectors (residential RES, commercial COM, agriculture AGR, industrial IND, transportation TRA), plus a non-energy use of energy/material products NEU, and two energy/supply sectors (electricity ELC and upstream/refinery UPS). New technologies are generally the same as those used in the Western Europe MARKAL model used in Kanudia et al. (2005).

The model includes 42 demands for energy services (19 in residential/commercial, 16 in transportation, 6 in industry, 1 in agriculture), such as vehicle-kilometers traveled by car, tonnes of aluminum to produce, etc. Price-elasticities of demands are also accounted for, so that the model captures a major element of the interaction between the energy system and the economy, and therefore, it goes beyond the optimization of the energy sector only since both the supply options and the energy service demands are endogenously computed by the model. Of course, this still falls short of computing a general equilibrium: to do so would require a mechanism for adjusting the main macroeconomic variables as well, such as consumption, savings, employment, wages, and interest rates, which the model does not represent.

The reader may refer to Labriet et al. (2004) and Kanudia et al. (2005) for more information on the general philosophy, equations and structure of the model. The rest of this section focuses on the specific characteristics of ETEM-SWI.

4.1. The existing energy system

The calibration of the model to an initial year reflecting historical data is a crucial task for building ETEM-SWI as well as any MARKAL model. Indeed, this calibrated initial energy system defines the existing stock of energy equipment, which, combined with the available future technologies and the primary energy potentials, will influence the model's future energy decisions. The fuel consumption per sector (Table III) and the secondary energy production (electricity sector, refinery) are based on various Swiss national statistics[5] for 2000 or

[5] National statistics from OFEN (2000b); electricity related data from OFEN (2000c, 2000d), and Prognos (2000); industry data from BasicAG (1996); buildings data from Brunner et al. (2001) and Kessler and Iten (2003); transportation data from OFEN (2000a) and Jochem et al. (2002); and emissions data from UNFCCC (2002).

Table III. Sectoral energy consumption used in ETEM-SWI in 2000 (TJ)

	Oil	Elec.	Gas	Coal	District heating	Biomass	Other renew	Total
RES	121.5	56.8	37.9	0.4	5.1	8.54	3.5	233.6
IND	44.8	63.9	36.9	5.3	5.3	19.7	0.1	176.0
COM	52.5	55.2	20.4	0.0	3.1	3.3	0.6	135.1
TRA	294.6	9.2	0.2	0.0	0.0	0.0	0.0	304.0
NEU	16.4	0.0	0.0	0.0	0.0	0.0	0.0	16.4
NS[a]	4.7	0.0	5.3	0.0	0.0	0.0	0.0	10.0
SD[b]	5.7	3.4	0.0	0.0	0.0	0.9	0.4	10.4
Total	540.2	188.5	100.7	5.7	13.5	32.3	4.6	885.6

[a]NS: non-specified.

[b]SD: statistical difference, including agriculture.

Table IV. GDP and population projections for Switzerland

	2000	2010	2020	2030	2040	2050
GDP (billions US$2000)	247	306	358.6	418.6	475.8	517
Population (millions)	7.2	7.3	7.4	7.4	7.3	7.2

on the energy statistics provided by IEA (2002b) if national statistics are not available. It must be noted that no primary energy production exists in Switzerland. The calibration of the residential sector is detailed in section 5.2. The assumptions related to the other sectors are available upon request.

4.2. The projections of demands

The projections of end-use demands result from economic and demographic drivers (see table IV) applied to the 2000 values in conjunction with assumptions on the sensitivity of service demands to the drivers, so that the projections are calibrated to the available national statistics. Transportation demands are based on Jochem et al. (2002) and OFEN (2000a); industry demands are based on BasicsAG (1996); by default, agriculture, residential and commercial sectors use the same sensitivity of service demands to the drivers as the Western Europe MARKAL model (Kanudia et al., 2005).

4.3. Techno-energy assumptions

This section describes the most important techno-energy characteristics used to model the Swiss energy system. First, given the relatively small size of the Swiss economy, we assume that changes in the level of Swiss exports and imports have no effects on the prices of internationally traded energy commodities. The latter are therefore exogenously fixed. Second, in the electricity sector both the nuclear production and the level of imports/exports are crucial in describing the future electricity system as well as the future GHG emissions of Switzerland. As regards nuclear power plants, we adopt the base case scenario proposed by Prognos (2000), assuming that the nuclear plants operate until the end of their lifetime (50 to 60 years). The installed nuclear capacity is 3.08 GW until 2015, decreases to 2.08 GW in 2025 (closure of Beznau I, II and Mühleberg between 2020 and 2025), and no nuclear capacity remains from 2040. Nuclear plants are partly replaced by combined cycle gas/oil plants in the reference scenario, and by wind plants when CO_2 emissions are limited. As regards electricity trade, the amount of exports and the minimal level of imports are fixed, reflecting the expected evolution of the purchasing agreements. The level of exports and the price of exports and imports are fixed to the levels proposed by Prognos (2000), while the minimal level of imports is smaller than the projections proposed by Prognos (2000), but the model is kept free to decide to import more electricity depending on carbon constraints and electricity prices. The effects of nuclear production and electricity trade on the CO_2 emissions deserve more attention in future work (sensitivity analysis).

In transportation, the minimal shares of natural gas (5% in 2050) and electricity (3% in 2050) in the total energy consumed by cars and light trucks are exogenously controlled. These constraints aim at reflecting the transportation policies in favor of alternative fuels either already decided or independent of climate policies. In industry, each demand segment includes: boiler, process heat, machine drive, electro-chemical process, and other processes. Feedstocks are included only in the chemical sub-sector. User-defined explicit constraints account for non-economic consumer behaviors that are outside the scope of the model. They limit the speed of energy and technology changes, and are progressively relaxed in future periods, so that enough flexibility is available for energy substitution and technology change. But recall that the industry-related CO_2 emissions as well as the abatement potential are very small. Finally, the assumptions related to the residential sector are described in section 5.2, since this sector is at the heart of the proposed coupling between ETEM-SWI and GEMINI-E3.

Table V. Electricity production by fuels, imports and exports in the base case (TWh)

	2000	2010	2020	2030	2040	2050
Mix gas/oil	0.00	0.00	0.00	0.00	3.61	3.89
Gas	0.28	0.28	0.00	0.00	0.00	0.00
Oil	0.00	0.00	0.00	0.00	0.00	0.00
Nuclear	25.83	25.83	23.33	17.50	0.00	0.00
Hydro	37.22	37.22	37.22	37.22	39.44	39.44
Biofuels	1.39	1.11	1.94	2.78	3.06	3.61
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Total	64.72	64.44	62.50	57.50	46.11	46.94
Exports	47.30	36.06	26.67	19.39	17.97	17.97
Imports	37.00	34.03	25.53	17.03	16.67	16.67

5. The hybrid model

The basic idea is to create a dialogue between the two complementary models. On one side, we use a reduced version of the CGE model, GEMINI-E3S, where the residential sector is removed and will be exogenously defined by a bottom-up model. On the other side, we use a reduced ETEM-SWI, called ETEM-RES, that represents only the residential sector, and where projections of useful energy demand, fuel prices and carbon price (tax) are provided by GEMINI-E3S. Rather than endogenizing energy demand by using price elastic demand formulations as in Loulou and Kanudia (2002), we obtain energy demands and the associated prices directly from the CGE model. In this section, we describe briefly the two reduced models, and the coupling technique.

5.1. The reduced GEMINI-E3S Model

For the coupling of GEMINI-E3 with a bottom-up model we use an aggregated version of the model in 6 regions rather than 21 (see table VI). The reference case for the different regions is closely calibrated on projections of CO_2 emissions, energy consumption, GDP, and population provided by EIA (2003a) for the years 2000 to 2025. After 2025, we have supposed a convergence of GDP growth to 2% per year for developed regions and 2.5% per year for developing regions at the end of the baseline projection. World greenhouse gas emissions are projected to reach 13Gt of carbon equivalent in 2020 and 16GtC equivalent in 2050 (Bernard et al., 2004a).

In the case of Switzerland, we have defined a baseline scenario that includes existing laws and regulations that have an impact on future domestic CO_2 emissions (Bernard et al., 2004b). This baseline is fully consistent with population, GDP, energy consumption, and CO_2 emissions growth projected by the Swiss government in a scenario "with measures implemented" (Bundesamt fur Energie, 2001; UNFCCC, 2002). This baseline scenario is also comparable with the one obtained from ETEM-SWI and ETEM-RES (see below).

Introducing energy consumption from ETEM-RES model needs two steps. The first step is to separate household energy consumption into residential and non-residential (mainly transportation). We have supposed that household consumptions of coal, natural gas and electricity are totaly used for residential purposes. For refined petroleum consumption we have to breakdown energy consumption between transportation and housing (mainly heating). We have used energy consumptions from IEA energy balances (OFEN, 2000b) and energy prices (IEA, 1998). The second step is to modify the standard Stone-Geary utility function (see equation (6) in section 3). The solution retained is to subtract from total household consumption (HCT_r) the purchase of energy for residential purposes, and to apply the Stone-Geary utility function to this new aggregate. This yields the following equation for non-energy consumption[6]:

$$HC_{ir} = \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k (PC_{kr} \cdot \phi_{kr}) - \sum_l \left(PC_{lr}^R \cdot HC_{lr}^R\right)\right] \quad \forall i = 6, ..., 14 \ and \ r = 3 \qquad (7)$$

where PC_{lr}^R and HC_{lr}^R represent the price and consumption of energy for residential activities.

For coal, natural gas and electricity consumption we replace the standard formula by the variable computed on the basis of ETEM-RES results:

$$HC_{ir} = HC_{ir}^R \qquad \forall i = 1, 2, 3, 5 \ and \ r = 3 \qquad (8)$$

where HC_{ir}^R are computed by the following equation :

$$HC_{ir}^R = \overline{HC_{ir}^R} \cdot \frac{CF_{ir}}{\overline{CF_{ir}}} \qquad \forall i = 1, ..., 5 \qquad (9)$$

where $\overline{HC_{ir}^R}$ represents residential energy consumption in the reference case in volume (i.e. in dollars at constant price), and $\overline{CF_{ir}}$ and CF_{ir}

[6] where i, r respectively stand for sectors and regions (i.e. $r = 3$ stands for Switzerland, see table VI).

Table VI. Dimensions of the GEMINI-E3S Model

Countries or Regions		**Sectors**
		Energy
Germany	DEU	01 Coal
France	FRA	02 Crude Oil
Switzerland	CHE	03 Natural Gas
Italy	ITA	04 Refined Petroleum
Other European Countries	OEU	05 Electricity
Rest of World[b]	ROW	***Non-Energy***
		06 Agriculture
		07 Mineral products
		08 Chemical Rubber Plastic
		09 Metal and metal products
		10 Paper Products Publishing
		11 Transport n.e.c. (road and railway)
		12 Sea Transport
		13 Air Transport
		14 Other Goods and services

[b] All countries not included elsewhere.

are the energy consumptions (in joules) computed by ETEM-RES in the reference case and in the policy scenario (see section 5.3). We thus apply in GEMINI-E3S percentage changes computed by the ETEM-RES model for energy consumption.

Finally we have to breakdown households' consumption of refined petroleum into transport and residential purposes (HC_{ir}^R) :

$$HC_{ir} = HC_{ir}^R + \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k \left(PC_{kr} \cdot \phi_{kr}\right) - \sum_l \left(PC_{lr}^R \cdot HC_{lr}^R\right)\right] \; i = 5 \; and \; r = 3 \tag{10}$$

ϕ_{ir} and β_{ir} are recalibrated on the basis of this new system of equations.

5.2. The reduced ETEM-RES Model

ETEM-RES consists of the residential sector of ETEM-SWI. It includes 11 demand segments which cover the needs in energy for the housholds (excluding personal transportation): heating, cooling, lighting, cooking, water heating, refrigerators and freezers, cloth washers, cloth dryers, dish washers and miscellaneous electric energy. The existing total energy consumption by the residential sector is based on OFEN (2000b) and on the IEA database (IEA, 2002a). Table VII shows the exogenous fuel split across the different end-use segments, inspired by Brunner et al. (2001) for electricity, by Kessler and Iten (2003) for space and water heating, and by the Western Europe MARKAL model as used in Labriet et al. (2004) and Kanudia et al. (2005) when Swiss statistics were unavailable.

For each end-use segment, technologies are in competition to satisfy the demand. For example, lighting may be satisfied by incandescent lamps, halogens, fluocompact lamps, etc.; or space may be heated with standard natural gas burner, improved natural gas burner, natural gas heat pump, geothermal heat pump, woodstoves, etc.

Technologies are characterized by their efficiency, annual utilization factor, lifetime, investment and operation costs. New technologies progressively replace existing technologies when they are cost-efficient (competitive in terms of comparison of NPVs) and the latter reach the end of their lifetime or when environmental policies force such a replacement. However, some exogenous constraints are added to reflect consumer behaviors and to avoid any abrupt and improbable technology change: they control either the energy mix of end-use consumptions (e.g. minimum level of electric technologies in cooling), or the penetration of some technologies (eg. minimum level of standard electric heat pump cooling). The constraints are progressively relaxed in future periods. Finally, a delivery cost for natural gas is added to account for new investments in distribution infrastructure.

Table VII. Fuel split across energy end-uses in residential sector (%)

	NGA	DST	HFO	KER	COA	LPG	BIO	ELC	HET	GEO	SOL
Space heating	79	86	100	100	89.9	68	97.7	17	100	85.9	
Space cooling								5		14.1	
Water heating	16	14			8.8	23	2.3	10			100
Freezers								14			
Clothes Drying								6			
Cooking	5				1.3	9		5			
Clothes washers								1			
Dish-washer								1			
Other Energy		0				0			0		
Misc. Elc Energy								32			
Lighting								9			

5.3. The Coupling technique

5.3.1. *Possible dialogue between the two types of models*

One possible way to couple a CGEM and an ETEM would involve an exchange of information in one direction (from CGEM to ETEM) concerning useful demands and imported energy prices[7] and in the other direction (from ETEM to CGEM) about marginal abatement cost (MAC) curves[8]. Unfortunately this approach is confronted to serious implementation difficulties when it comes to the correct evaluation of the MAC curves needed to run the CGEM. The marginal costs computed by ETEM are related to the dual values associated with emissions upper bounds. They are based on the intertemporal perfect foresight optimization scheme implemented in MARKAL. Often these dual values in ETEM change drastically from one period to the next and it is not obvious to derive the stable MAC curves needed for each time period in the CGEM. Furthermore, it is not the dual value associated in ETEM with one level of abatement that is needed but the whole curve of dual values for different possible abatement levels. In Lavigne et al. (2000), a method is proposed for exchanging local information concerning these MAC curves between models[9]; however we are not aware of a successful use of these methods to couple an ETEM and a CGEM[10].

To circumvent these difficulties we have implemented a coupling via a different type of dialogue between the two models. The CGEM still sends estimates of useful demands and energy prices to the ETEM; it also defines the carbon taxes that will be applied in the ETEM optimization run[11]. For the CGEM the ETEM is a "black box" which sends back a set of final energy demands and carbon emissions from the residential sector. This way we use marginal abatement costs from the CGEM for all sectors, except for the housing sector. For housing, we use the ETEM to mimic the technology/energy choices of economic agents

[7] The World economic model should provide information about the world demand for different energy forms and hence an indication of the relative prices of different forms of imported fuels. The Swiss CGEM will provide information about economic activity in the different sectors and hence the useful demands.

[8] MAC curves are an essential part of CGEM when they address the issue of climate policy assessment. This information summarizes the technical substitutions that should take place to obtain the desired emissions abatement.

[9] They considered in this way the linkage of linear models of supply and demand.

[10] The study realized at MIT attempted a linkage between the transportation sector in MARKAL and the CGEM EPPA (Schafer and Jacoby, 2003). The link was very weak, as the MARKAL model only served to delineate, through a sequence of runs, a global shape for the MAC curve.

[11] Note that the ETEM run is made without emissions constraints, but realizes cost minimization under a given carbon tax system.

in the residential sector facing market prices and carbon taxes. In the CGEM, the modeling of household consumption – which is based on a Linear Expenditure System (LES) corresponding to the Stone-Geary utility function – has to be modified (see above). In GEMINI-E3S, households' energy consumption for housing is set exogenously on the basis of the fuel mix obtained from ETEM. Non-energy consumption for housing is supposed to change in response to changes in relative household consumption prices (including fuel prices) but is not modified by the energy mix resulting from technology choices in ETEM.

5.4. The coupling realized in this case study

The coupling variables are listed in Table VIII.

Table VIII. List of coupling variables

$T_{t,k}$	:	carbon taxes
$PE_{t,k}$	:	energy prices
$CE_{t,k}$	:	useful energy demand in the residential sector,
$CF_{t,k}$	:	final energy consumption by fuel type
$C_{t,k}$	:	carbon emissions
t	:	stands for time period
k	:	stands for iteration number

Since the energy prices $PE_{t,k}$ are not expressed in the same unit in the two models we apply a "percentage change" procedure. For example if GEMINI-E3S computes that the price of coal is increasing by 10% with respect to the baseline we applied the same variation for the price of coal used by ETEM-RES. The same procedure is used for $CF_{t,k}$ (see equation 9). The residential useful energy demand implemented in ETEM-RES, $CE_{t,k}$, is indexed on total household consumption computed by GEMINI-E3S. So we suppose that the budget share of residential services (cooking, lighting, heating, etc) does not differ from the baseline scenario. The procedure to couple the two models is summarized below and in Figure 3:

1. Run GEMINI-E3S on the basis of an emission reduction profile (see Policy Scenarios) in order to get starting values for carbon taxes $T_{t,0}$, energy prices $PE_{t,0}$, and useful energy demands in the residential sector $CE_{t,0}$.

2. Run ETEM-RES using values for $T_{t,0}$, $PE_{t,0}$, and $CE_{t,0}$ from GEMINI-E3S, and get starting values for final energy demands $CF_{t,0}$ and carbon emissions $C_{t,0}$ in the residential sector.

3. Run the GEMINI-E3S model with estimates for $CF_{t,0}$ and $C_{t,0}$ from ETEM-RES in order to get new carbon taxes $T_{t,1}$, energy prices $PE_{t,1}$ and useful energy demand $CE_{t,1}$ in the residential sector up to 2050.

4. Run ETEM-RES using the new data from GEMINI-E3S ($T_{t,1}$, $PE_{t,1}$, and $CE_{t,1}$), and obtain new estimates for the fuel mix $CF_{t,1}$ and carbon emissions $C_{t,1}$.

5. Run GEMINI-E3S with $CF_{t,1}$ and carbon emissions $C_{t,1}$ and get $T_{t,2}$, $PE_{t,2}$, and $CE_{t,2}$; etc...

6. Use the stopping criterion[12] defined in Eq. (11) for convergence, where $T_{t,k}$ represents carbon prices at time t from GEMINI-E3S in iteration k.

$$\Phi = \sqrt{\sum_{1}^{t}(T_{t,k} - T_{t,k-1})^2} \leq \epsilon = 0.01 \qquad (11)$$

At convergence, one has a system of carbon taxes determined by the CGEM that yields the desired abatement levels in the whole economy and for which, the carbon emissions and fuel mix in the residential sector is the one selected by economic agents when they minimize the total discounted cost.

5.5. Scenarios and Results

5.5.1. *Reference Case*

The reference case represents a situation where no energy or environment policies apply beyond the already enforced laws and regulations. As described previously, the reference case is built on three essential assumptions that are likely to have an effect on energy consumption and carbon emissions:

– The economic and demographic projections (see section 4.2);

– The gradual increase of energy efficiency, in response to energy legislations and energy efficiency programmes such as the Federal programm “Energy Switzerland”;

– The level of nuclear power plants and of exports/imports (see section 4.3).

[12] A gap $\epsilon = 0.01$ means that one declares convergence when two successive tax schedules differ by less than one cent other the whole period.

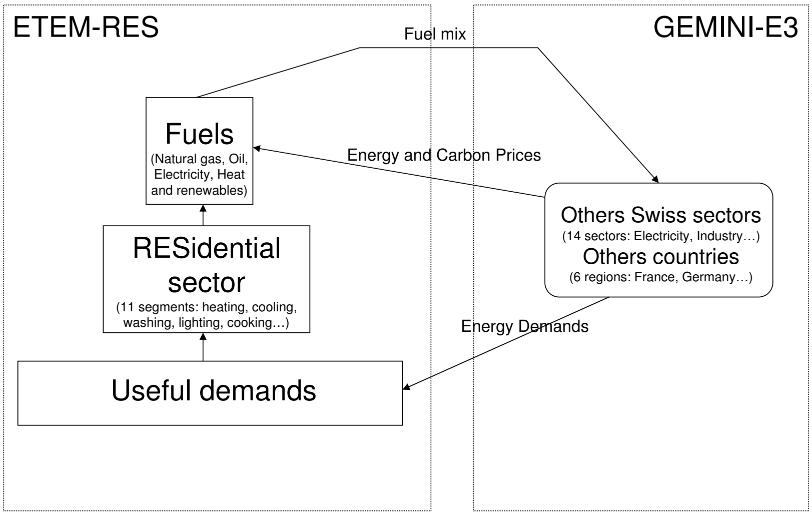

Figure 3. ETEM-RES and GEMINI-E3S Overview

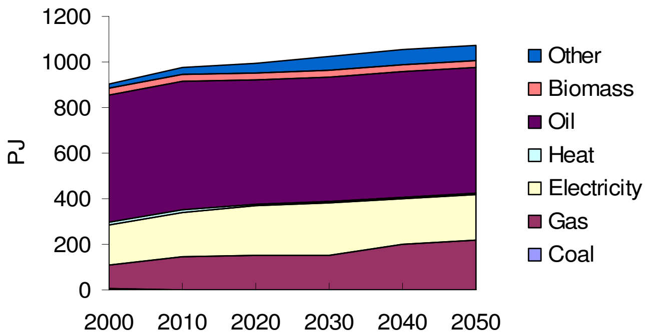

Figure 4. Energy mix obtained with ETEM-SWI in the reference case

Figures 4 and 5 illustrate the resulting energy mix and carbon emissions obtained from ETEM-SWI and used to calibrate the reference case in GEMINI-E3.

5.5.2. *Policy Scenarios*

In this study, we selected two policy scenarios to mitigate global GHG emissions constraint in the long run:

- **S20**: world CO_2 emissions are assumed to be reduced linearly in order to obtain a 20% reduction from the reference case by

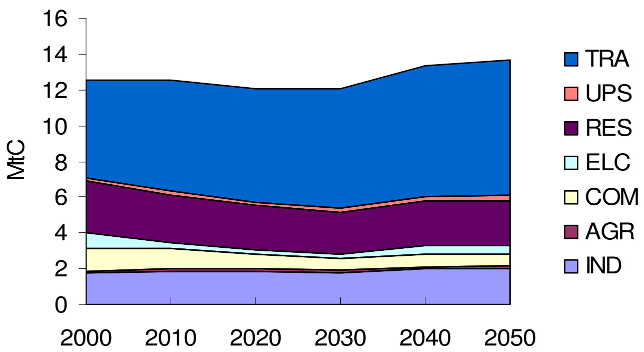

Figure 5. CO_2 emissions obtained with ETEM-SWI in the reference case

2050. For simplicity, we assume that emissions quotas are allocated among countries in proportion to emission in the reference case (20% target for each region, including Switzerland)[13]. Finally, each country or region is supposed to reach its reduction target through a uniform CO_2 tax without exemptions and without international emissions trading.

– **S40**: This scenario is the same as the previous one, except that the reduction target is 40%.

5.5.3. *Simulation results*

In table IX we show that convergence has been reached after four iterations under the two policy scenarios. In Figure 6, we plot carbon taxes $T20_{t,k}$ and $T40_{t,k}$ obtained from 2000 to 2050 under the 20% and the 40% reduction target scenarios, respectively. $T20_{t,0}$ and $T40_{t,0}$ correspond to carbon taxes obtained from GEMINI-E3S with starting values $CF_{t,0}$ and $C_{t,0}$ from ETEM-RES. $T20_{t,4}$ and $T40_{t,4}$ are carbon taxes resulting from the last iteration. As shown on the graph, carbon taxes are expected to grow in Switzerland from \$70/tC in 2010 to \$414/tC in 2050 in the S20 scenario. When CO_2 emissions are assumed to be reduced by 40% (S40), the carbon tax rises from \$138/tC in 2010 to \$1362/tC in 2050. At an international level (see table X) the results confirm (Kram and Hill, 1996; Bahn et al., 1998) that the marginal abatement cost (i.e. the carbon tax) for Switzerland is the highest even in comparison to other European countries.

[13] The equity issue related with the sharing of the costs of the long term GHG emissions target across countries and regions have been considered elsewhere (Bernard et al., 2004a).

Table IX. Values of Φ in the two policy cases

	S20	S40
$k = 1$	121.13	481.70
$k = 2$	19.22	12.87
$k = 3$	2.77	0.05
$k = 4$	0.01	0.006

Table X. Carbon taxes by region in the two policy cases in 2050 (in \$/tC)

	S20	S40
Switzerland	414	1362
Germany	197	755
France	292	1224
Italy	282	1106
Other European Countries	111	462
Rest of the World	45	174

In Figures 7, one can observe that the contribution of the Swiss residential sector to the reduction effort is rather low. In the S20 scenario, CO_2 emissions are reduced by 13% compared to the reference emissions in 2050. In the S40 scenario, CO_2 emissions are 26% below the reference emissions in 2050. By taking into account substitution and reduction options in the whole economy, the coupled model finds that abatement costs are relatively high in the residential sector compared to the other sectors and that emissions might be reduced at lower cost in other sectors.

One should also note that the CO_2 emissions targets are reached through inter-fuel substitutions rather than a drastic reduction of residential energy consumption. Compared to the reference case, energy consumptions are reduced by only 2.5% and 5% in 2050 in the S20 and S40 scenarios, respectively. It means that CO_2 emissions reductions are realized through changes in the fuel mix in the housing sector. Indeed, the 20% reduction required in the S20 scenario is mainly obtained through a switch from natural gas to electricity and biomass (see Figure 8). The basic story is the same when the carbon constraint is more severe (S40), except for a lower share of natural gas and a greater penetration of geothermal energy (i.e. heat pumps for space heating, space cooling, and to provide hot water).

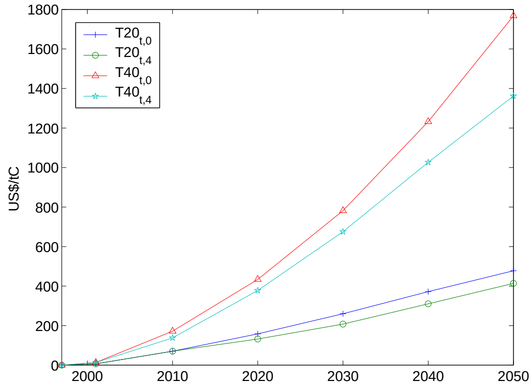

Figure 6. Carbon taxes in Switzerland under the two policy cases, 2000-2050 (in $/tC)

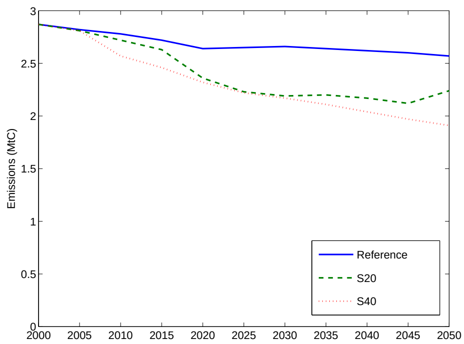

Figure 7. CO_2 emissions in the residential sector in the reference case, S20, and S40, 2000-2050 (in MtC)

In Figures 9 and 10, one can see that almost 70% of the demand for energy services (useful energy demand) in the housing sector would be for heating space in 2050. In the S20 scenario, space heating is mainly provided with natural gas (55%) and oil (32%). Geothermal energy and biomass represent only 4.5% and 2.8% of total energy consumption for space heating in 2050. When the emissions constraint is higher (S40), the consumption of natural gas for space heating is reduced (41%), and geothermal energy increases from 4.5% to 16.7%[14].

[14] The observed stability of oil share might seem counterintuitive and deserves some explanations. In the model, the consumption of oil for space heating and water heating is controlled by exogenous constraints, reflecting that fuel substitution associated to these service demands depends not only on economic factors but

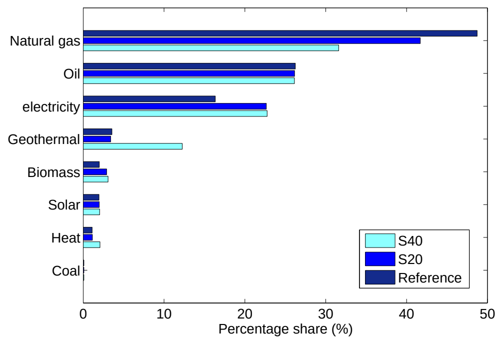

Figure 8. Energy consumption by fuel type in the residential sector in the reference case, S20, and S40, 2050 (in %)

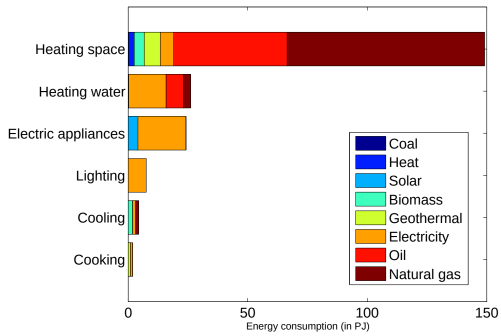

Figure 9. Useful energy demand under the 20%-reduction scenario, 2050 (in PJ)

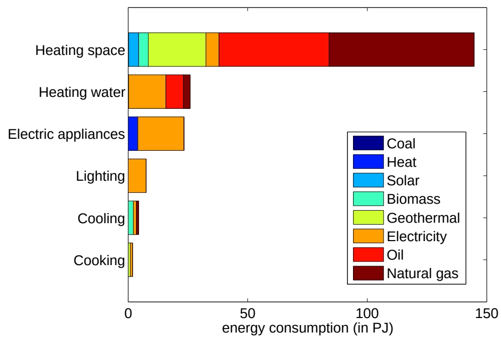

Figure 10. Useful energy demand under the 40%-reduction scenario, 2050 (in PJ)

6. Comparing GEMINI-E3, ETEM-ED-SWI, and the hybrid model

In order to evaluate the effects of coupling ETEM-RES and GEMINI-E3S. It is interesting to compare the simulation results coming from the hybrid model with the ones from the standard version of the two models, GEMINI-E3 and the ETEM model with elastic demand (ETEM-ED-SWI).

As shown in table XI, the carbon tax with GEMINI-E3 and the coupled model are quite similar even if the tax is always smaller with the GEMINI-E3 model. In the S40 scenario, the residential carbon emission abatement would be equal to 57% with the GEMINI-E3 model whereas the reduction would only be 26% with the hybrid model. The ETEM-RES module gives less substitutability of fossil fuel consumption in response to an increase of carbon taxes. Carbon prices must be increased more in the hybrid model in order to reach the same carbon emission reduction in percentage. A higher burden is thus put on the other energy consumption in the hybrid model (i.e. agricultural, industrial and transport energy consumption). The changes in energy consumption in the housing sector are also quite different in the two models, even if the ranking of the energy sources is similar: the two models find that electricity would be less affected and that natural gas would be more depressed. For natural gas and refined petroleum consumption GEMINI-E3 gives more important reductions: -35% with GEMINI-E3 against -5.4% with the hybrid model for petroleum products in the scenario S40 and -77% against -38% for natural gas. Electricity consumption goes the opposite way: the hybrid model yields an important increase of electricity consumption (more than 30% in the two cases) whereas electricity consumption slightly decreases in the GEMINI-E3 configuration (less than 5% in the S40 scenario).

Simulations results show that marginal abatement costs tend to be higher in ETEM-SWI than in GEMINI-E3 in all sectors. At the same time, marginal abatement costs are relatively low in the residential compared to other sectors in the two models. Consequently, when the two models are combined in the hybrid model, one gets a lower contribution to the reduction effort from the residential sector compared to the case where the two models are used separately. In the S40 scenario, residential carbon emissions might be reduced by 26% in the hybrid model against 58% in the GEMINI-E3 model and 53% in ETEM-ED-SWI.

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also on non-market parameters. Here, this constraint acts as a lower bound for oil consumption.

Table XI. GEMINI-E3 *versus* Hybrid Model in 2050

	Scenario S20		Scenario S40	
	Gemini-E3	Hybrid	S40 Gemini-E3	Hybrid
Carbon Tax (in $/tC)	342	414	1142	1362
Residential Energy Consumption*				
Coal	-64.3%	-0.3%	-69.5%	-3.3%
Petroleum products	-14.6%	-2.8%	-35.2%	-5.4%
Natural Gas	-55.3%	-16.5%	-77.7%	-38.5%
Electricity	-1.4%	35.1%	-4.4%	32.2%
Residential Carbon Emission*	-36.2%	-11.4%	-57.6%	-26.1%

* Percentage change from the reference scenario in 2050.

Table XII. ETEM-ED-SWI *versus* Hybrid Model in 2050

	% of total emission reduction		% of reference emissions	
	S20	S40	S20	S40
ETEM-ED-SWI				
Agriculture	0%	0%	0%	0%
Commercial	0%	2%	-1%	-15%
Electricity	10%	7%	-75%	-82%
Industry	12%	16%	-24%	-44%
Residential	8%	24%	-12%	-53%
Transport	70%	51%	-36%	-45%
Total	*100%*	*100%*	*-28%*	*-45%*
Hybrid model				
Residential	12%	12%	-13%	-26%

In table XII, we compare numerical results from the hybrid model with results obtained from ETEM-ED-SWI when S20 and S40 carbon taxes are applied. Several remarks apply. First, transportation plays a crucial role in the overall emission reduction of Switzerland in both scenarios: the substitution of oil by biomass and by natural gas to a lesser extend, as well as the penetration of more efficient oil vehicles are observed, while electricity remains unchanged compared to the baseline scenario. Second, it is interesting to note that the share of residential in the overall emission reduction is higher in previous periods under S20 scenarios (for example, it reaches more than 65% of the reduction in 2025). Indeed, fuel substitution in residential and industry sectors is preferred to fuel substitution in transportation when the low CO_2 tax is applied. It means that the penetration of biomass vehicles becomes a competitive abatement option in the short run only under higher levels of CO_2 tax. In other words, abatement options in residential might represent a transition to alternative transportation technologies. Finally, emissions are strongly reduced in the electricity sector (gas/oil combined cycle plants are replaced by wind plants) in both scenarios, while the emission reductions by industry and housing sectors are far larger when S40 is implemented. However, it must be noted that large reductions from the reference case (right-hand columns of table XII) may represent small absolute emission reductions (e.g. emissions reduction from the electricity sector) (left-hand columns of table XII).

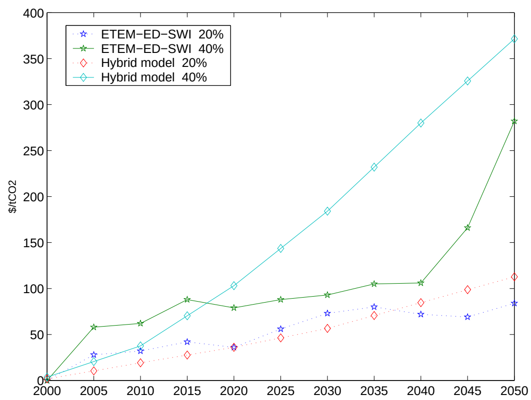

Figure 11. CO_2 Taxes under the 20% and 40% reductions targets in ETEM-ED-SWI and the Hybrid model

The price-induced reduction of elastic demands in ETEM-ED-SWI contributes to reduce the emissions by 2.5% and 9.6% in 2050 under S20 and S40 respectively, in comparison with scenarios where energy demands are not elastic to their own price. The highest reduction of energy demand occurs in transportation, more particularly in aviation. In residential, demand reductions occur for electric appliances (up to 5% reduction), hot water (up to 3% reduction), and for the other end-use segments to a lesser extend (up to 1.5%). The price-induced reduction of energy demands reduces the resulting CO_2 tax computed by ETEM-ED-SWI by more than 50% at several periods[15]. In Figure 11, we compare CO_2 taxes obtained from the hybrid model under S20 and S40 with the ones computed by ETEM-ED-SWI under the same conditions. The resulting CO_2 taxes appear to be higher in the short term in ETEM-ED-SWI than in GEMINI-E3, but lower in the long term.

7. Conclusion

In the battery of models developed for the assessment of climate policy, it is now considered "good practice" to use CGEMs to represent the macro-economic adjustments and ETEMs to detect efficient technology and energy-option choices. The question of how to connect together these two modelling tools in order to obtain a better assessment of climate policies is not yet fully answered. In this report we have presented a CGEM and an ETEM adapted to the analysis of the economics of climate in Switzerland. We have also presented a scenario built from the use of an hybrid model composed of modules borrowed from the CGEM and the ETEM. This experiment has illustrated a way to establish a useful dialogue between these two classes of models. More precisely:

- The introduction of the ETEM-RES model in GEMINI-E3 allows to take into account a more appropriate representation of energy consumption based on a precise technological representation of the energy system. It also preserves the consistency of the CGEM, i.e. general equilibrium interactions at the national and international levels[16].
- This method allows an easy introduction of technological innovation in the energy fields and, consequently, permits the analysis of the implication of future energy technology on a carbon abatement strategy.
- The approach can also be used to test mixed or hybrid strategies combining tax instruments and norm regulation (i.e. policies and measures like efficiency norms on household equipment).

Some methodological aspects of this work need to be discussed. For example, the way we represent the price elasticity of useful energy demands in the residential sectors might be improved. As explained above,

[15] Given the effect of the price elasticity of energy demands, the estimation of the numerical values of elasticities deserves more attention in future work.

[16] On international markets of goods, and in particular the energy market.

from the CGE model, one can only get a unique elasticity parameter based on aggregate consumption. One possibility would be to use an elastic version of ETEM, as developed in the world MARKAL model and following the approach proposed by Loulou and Lavigne (1996), and to implement only energy prices and carbon taxes obtained from the CGE model.

Other methodological aspects regarding the computation of MAC curves in the two models need to be considered. In a CGE model, marginal abatement costs reflect a change in terms of trade, and a domestic cost (deadweight loss) which can be broken down into two components (Bernard and Vielle, 2003). The first is a pure cost of carbon taxation, which is the integral below the curve of carbon tax. It is the domestic cost that would emerge without initial distortion in the economy. The second component is the additional cost (whether positive or negative) resulting from initial distortions in the economy (Babiker et al., 2003). Sectoral models can only estimate the pure cost of carbon taxation. In Bernard and Vielle (2003), it is shown that carbon tax curves obtained from a CGE model (GEMINI-E3) and a bottom-up model (POLES) may be close to each other. However, modeling results greatly differ when tax distortion effects are accounted for in the CGE. In this paper, we consider only the pure cost of carbon taxes. Other experiments are required to assess the impact of pre-existing energy taxation on technology choices in ETEM-SWI and welfare change.

Further developments are also envisioned to treat other sectors of the Swiss economy, like e.g. transportation or electricity production, in a similar way. It would require to address the issue of making assumptions on the future of nuclear production in Switzerland, and international trade in electricity. It would also imply to consider the uncertainty related to the availability and the costs of non-carbon backstop technologies such as electric vehicles, fuel cell cars, etc. Therefore, sensitivity analysis might be necessary.

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