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Sustainability, neutrality and beyond in the framework of Swiss post-2012 climate policy

By
André Sceia, Juan-Carlos Altamirano-Cabrera, Thorsten F. Schulz and Marc Vielle

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Sustainability, neutrality and beyond in the framework of Swiss post-2012 climate policy*

André Sceia, Juan-Carlos Altamirano-Cabrera,
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Abstract

Switzerland, as many developed countries, face a double problem for the next round of international negotiations on climate change. On the one hand, short term economic strategies would favor the implementation of a global carbon market that would minimize abatement costs globally. On the other hand, purchasing emissions certificates from developing countries does not prepare for the major technological and social changes that will certainly be required before the end of the century to avoid climate change. In this paper we use a coupled top-down bottom-up model to assess the impacts of a number of ambitious climate policies in Switzerland. We find that stringent policies with both domestic and total emission targets are affordable for a wealthy country like Switzerland. Such policies could not only put Switzerland in a leading position regarding climate change issues but also pave the way for its long term climate policies.

Keywords: Switzerland, Climate policy, Climate neutrality, Coupled CGE, Welfare economics
JEL Codes: C68, Q56, F18

1 Introduction

Currently there is an important discussion about what will be the shape of the international climate policies that will be enacted after 2012. Among the important issues being discussed, countries will have to decide upon the level of abatement they can achieve and to what extent to allow the use of flexibility mechanisms like global GHG emissions certificates markets. The decision to commit to a emission reduction target and to use or not flexibility mechanisms depends mainly on the expected welfare costs of the policie and on the short and long terms environmental objectives of the country. In this paper, we analyze four ambitious emission targets for Switzerland.

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First we consider an abatement of 50% by 2050 with respect to 2000 emissions level; a reference target for developed countries since it has been extensively discuss in the European Union.

Secondly, a sustainable approach that reflects the fact that the ultimate goal of post-Kyoto climate policies will be to stabilize greenhouse gas (GHG) emissions at sustainable levels. Recent international studies (IPCC, 2007) state that concentrations of 450ppm would limit the increase of temperature to acceptable levels (around 2°C) and, therefore, could be considered as sustainable. In order to limit the concentrations to those levels and taking into account the approach of contraction and convergence policies (ETHZ, 2008; Meyer, 2000), GHG emissions per capita would have to be globally limited to 1 tCO_2eq per annum by 2100. For developed countries, such a target is far from current levels of emissions per capita (7.2 tCO_2eq/cap in Switzerland in 2004), and for developing countries, it means that their development could not be based on the technologies that contributed to the development of industrialized countries.

Thirdly, the neutral approach advocates the offset of the totality of the emissions generated by a person, a company or a country. This idea is increasingly accepted among individuals and companies, however, it would represent a major step forward to extend the idea to a whole country. In the framework of the revision of its Swiss CO_2 tax, Switzerland has already mentioned the climate neutrality as a potential option for the future of Swiss climate policy (FOE, 2008). This neutrality could be mainly achieved by means of large purchases of CO_2 certificates, potentially jeopardizing the efforts to further improve the energy efficiency of Swiss infrastructures and technologies as well as change toward more sustainable behaviors of consumers and firms.

Fourthly, the zero-footprint approach which includes offsetting emissions embodied in imported goods. Supporters of a "neutral" Switzerland state that the transfers generated by the purchase of certificates will allow developing countries to achieve a more sustainable development path, in particular when considering that developing countries are producing an important share of high energy goods. In Switzerland, the share of embodied emissions in the Swiss net trade represents about 80% of the domestic emissions (Jungbluth et al., 2007). Going one step further and taking embodied emissions into account for setting emissions targets could revolutionizes the current approach to international climate negotiations, since, so far, the GHG emitted to produce goods are accounted in the producing countries, not in the consuming ones.

Moreover, regardless of how ambitious the Swiss emission target will be, if the abatement is manly achieved through the purchase of GHG emissions certificates and that the global price of he certificates is low, the country might not start the necessary upgrading of its infrastructures or see changes in the consumption patterns. Without a minimal domestic abatement, the four approaches above may sound like a solution which could only bring economic benefits in the short term. With that in mind, we also analyze policies that follow the same approaches but includes the additional requirement to have a 50% reduction of domestic emissions.

The objective of this paper is to assess the economic consequences of such polices on the Swiss economy, considering as illustrative example the residential sector. In order achieve the various objectives above, we combine the implementation of a linearly progressive Swiss GHG emissions tax with a global GHG emissions certificates market. In view of the size of Switzerland, the price of the certificates is mainly seen as being influenced solely by the emissions targets decided by in other regions. Therefore, we have considered tree different international scenarios. In each of them, the Swiss tax is either used to achieve a domestic abatement or to collect the revenue that would allow for the purchase of foreign GHG emissions certificates.

We use a coupled top-down bottom-up model that allows for a precise technological specifications in the Swiss residential sector, which encompasses a great potential for GHG emissions abatement, without loosing the national and global economic picture. The coupling between top-down and bottom-up models has already been explored in the literature (see, among other, Böhringer (1998); Drouet et al. (2005); Löschel and Soria (2007); Manne and Richels (1992); Pizer et al. (2003); Sceia et al. (2008); Schäfer and Jacoby (2006); Wing (2006). We have nevertheless followed an approach relatively different from those used by these authors. In Pizer et al. (2003), Schäfer and Jacoby (2006) and Löschel and Soria (2007) the coupling has been mainly carried out in the calibration phase of the modeling; bottom-up models were used to calibrate some of the parameters in the top-down models. Different from them, we have linked the models in the simulation phase. In Böhringer (1998) and Wing (2006), technology details have been directly incorporated in a CGE model. In contrast, we have worked with existing bottom-up and top-down models and tried to keep them as close as possible from their original formulation. Therefore, both models have been kept separate, while linking them with a coupling module. Manne and Richels (1992) incorporated a reduced CGE model in a bottom-up model. In contrast, we tried to keep our CGE as complete as possible, allowing for a more complete and realistic interpretation of the results for the forthcoming consultation procedure on the future of the Swiss CO_2 law. Finally, until now, the only coupling papers specifically targeted to the Swiss residential sector are Drouet et al. (2005) and Sceia et al. (2008). Drouet et al. (2005) have devised an hybrid model where the residential sector is completely removed from the top-down model and it is replaced by an exogenous and separate bottom-up model. Sceia et al. (2008) developed the earlier version of the model we use in this paper. We brought various improvement to the coupling procedure, the models as well as the calibration procedure.

We find that if international agreements aim at limited emission reductions, Switzerland could afford very stringent abatement targets without substantial welfare losses. In the case where developing countries would start contributing significantly to the abatement effort, even as late as in 2030, the impact of highly stringent policies becomes important, but getting on the track of sustainability could be affordable with a progressive GHG tax reaching around 140 USD_{2001}/tCO_2eq.

The paper is organized as follows: section 2 presents the models and the methodology, section 3 presents the policy scenarios, section 4 the results and section 5 concludes.

2 Models and methodology

2.1 GEMINI-E3

We use an aggregated version of GEMINI-E3, a dynamic-recursive CGE model with a highly detailed representation of indirect taxation, that represents the world economy in 6 regions and 18 sectors[1]. We defined the regions as follows: Switzerland (CHE), European Union (EUR)[2], other European and Euro-asian countries (OEU)[3], Japan (JAP), USA, Canada, Australia and New Zealand (OEC) and other countries, mainly developing countries (DCS). The model is formulated as a Mixed Complementarity Problem , which is solved using GAMS and the PATH solver (Ferris and Munson, 2000; Ferris and Pang, 1997). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-6 database (Dimaranan, 2007), that provides a consistent representation of energy markets in physical units and a detailed Social Accounting Matrix (SAM) for a large set of countries or regions and bilateral trade flows between them. Moreover, we have completed the data from the GTAP database with information on indirect taxation, energy balances and government expenditures from the International Energy Agency (International Energy Agency, 2002a,b, 2005), the OECD (OECD, 2005, 2003) and the International Monetary Fund (IMF, 2004). For Switzerland, we used data from 2001 input-output table devised at the Swiss Federal Institute of Technology (ETH) in Zürich (Nathani et al., 2006) which we transformed in the GEMINI-E3 format (Sceia et al., 2007). All the data on emissions and abatement costs for non CO_2 GHG come from the U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2006).

Previouly, GEMINI-E3 has been used to study the strategic allocation of GHG emission allowances in the enlarge EU market (Viguier et al., 2006), analyze the behavior of Russia with regard to the ratification process of the Kyoto Protocol (Bernard et al., 2003), assess the cost of implementation of the Kyoto protocol in Switzerland with and without international emissions trading (Bernard et al., 2005), or assess the effects of an increase of oil prices on global and GHG emissions (Vielle and Viguier, 2007).

Apart from a comprehensive description of indirect taxation, the specificity of the model is that it simulates all relevant markets: commodities (through relative prices), labor (through wages) as well as 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 "real" exchange rates can also be accurately modeled. GEMINI-E3 also calculates the deadweight loss for each region on the basis of the consumers' surplus and the gains or losses from the terms of trade.

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

In order to allow the calibration and the coupling of GEMINI-E3 with MARKAL-CHRES, we have replaced the Stone-Geary utility function by a nested constant elasticity of substitution (CES) function. The nesting structure is shown in Figure 1. Numbers in the figure refer to the products as presented in appendix B table 5. The σ_x refer to the elasticity parameter of each node. The version of GEMINI-E3 we use for this research only uses petroleum products as input in the transportation energy nest.

[1]The complete GEMINI-E3 represents the world economy in 28 regions (including Switzerland) and 18 sectors (see table 5 in appendix B for the detailed classification). All information about the model can be found at http://www.gemini-e3.net, including its complete description (Bernard and Vielle, 2008).

[2]refers to the European Union member states as of 2008

[3]includes other European countries, Russia and the rest of the Former Soviet Union excluding Baltic states

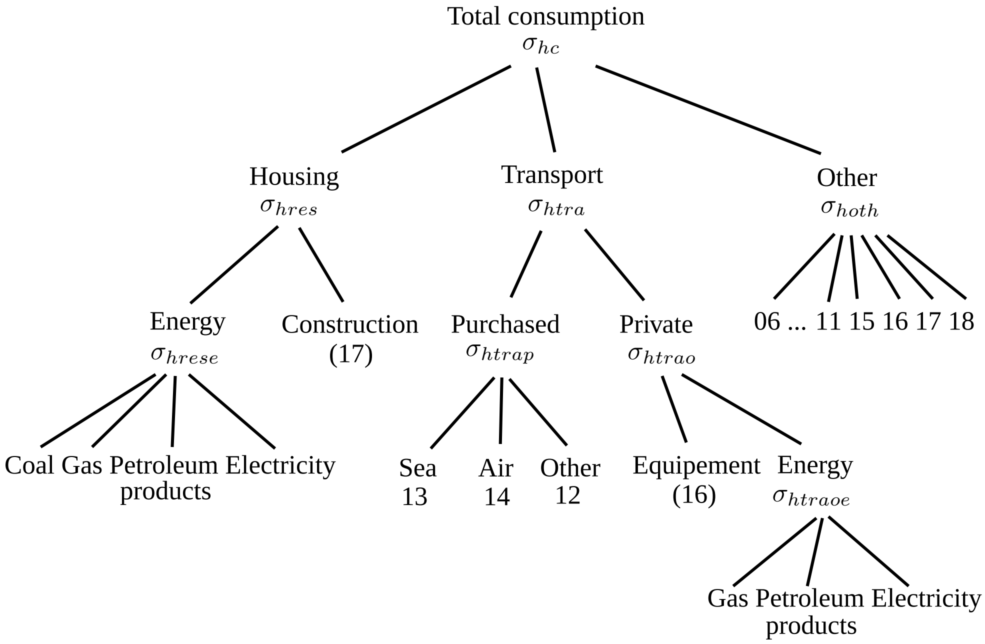

Figure 1: Structure of the households' nested CES utility function

We have also introduced an emission certificates market that allows for modeling a global cap and trade system. Each region receives annually an endowment of emission certificates, equal to the emission policy target. In Switzerland, we have also implemented an exogenous progressive GHG tax, independent from the global price of certificates that allows for higher domestic abatement.

2.1.1 Measuring the cost of GHG abatement

Climate policies are devised in order to avoid future welfare losses induced by the potentially costly damages and adaptation measures entailed by changes in climate if no mitigation effort is undertaken. It is not the aim in this paper to consider the tradeoff between adaptation and mitigation measures but rather to measure the costs for the society to abate GHG emission. Measuring the costs of climate policies and comparing their efficiencies can be done in various way. A simple approach consists in analyzing de variation of macroeconomic aggregates such as GDP or households' final consumption (HFC). Unfortunately, the variation of GDP and HFC does not account for the variation of relative prices induced by the introduction of a GHG tax. The households' surplus, either based on the compensative variation of income (CVI) or the equivalent variation of income is a more consistent and complete measure of the costs of climate policies (Bernard and Vielle, 2003). The households' surplus or total welfare gains (WG_t) at each period t can therefore be expressed as

$$WG_t = \Delta R_t - CVI_t, \tag{1}$$

where ΔR is the variation of income, mainly due to transfers trough international trade. The welfare gains vary greatly from the theoretical case of a close economy, where they are equal to the deadweight loss of taxation (DWL), to the case of an open economy having access to an emissions certificates trading market. In this later case, the total welfare gains can be expressed as

$$WG_t = DWL_t + GTT_t + EC_t, \tag{2}$$

where GTT and EC are respectively the gains or losses of the terms of trade and the net revenue from trading emission certificates. Assuming that trade balances are indeed balanced at each period and for each region, the GTT can be calculated as follow,

$$GTT = \sum_i (X^0_{i,t} \cdot \Delta P^X_{i,t} - M^0_{i,t} \cdot \Delta P^M_{i,t}), \tag{3}$$

where, for sector i and period t, $X^0_{i,t}$ is the baseline exports, $M^0_{i,t}$ the baseline imports, $\Delta P^X_{i,t}$ the export price variation between the baseline and the scenario and $\Delta P^M_{i,t}$ the import price variation. The sum of GTT and EC over all regions equal zero, since the global economy may be thought as a close economy. As a consequence, the world consumer surplus equals the world deadweight loss of taxation.

In order to present the total effect on the welfare of a specific scenario, we represents the sum of the various discounted values as a percentage of the sum of the discounted households final consumption, using a 5% discount rate.

2.2 MARKAL-CHRES

MARKAL models are perfect-foresight bottom-up energy-systems models that provide a detailed representation of energy supply and end-use technologies under a set of assumptions about demand projections, technology data specifications and resource potential (Loulou et al., 2004). The backbone of the MARKAL modelling approach is the so-called Reference Energy System (RES). The RES represents currently available and possible future energy technologies and energy carriers. From the RES, the optimization model chooses the least-cost combination of energy technologies and flows for a given time horizon and given end-use energy demands.

The MARKAL-CHRES is an energy model describing the Swiss residential energy system. It is based on the Swiss MARKAL model developed at the Paul Scherrer Institute (PSI) and previously used to analyze the Swiss 2000 Watt Society concept (Schulz et al., 2008), among others. MARKAL-CHRES comprises only a part of the complete Swiss model, being restricted to technologies related to the residential sector and treating final energy as being imported with exogenous prices. The model still contains 173 technologies using different energy sources (coal, oil, gas, electricity, wood, pellets and district heat). Resource costs and potentials as well as technology costs, potentials and characteristics vary over time.

Base year (2000) energy demand in MARKAL-CHRES is calibrated to International Energy Agency (IEA) and Swiss statistics. The model has a time horizon of 50 years until 2050, divided into eleven time steps each with a duration of five years (except the base year). The residential energy sector of the model includes 14 energy demand segments (see appendix B table 6). The most important segments are the Room-Heating (RH) segments which represent more than 70% of final energy demand. We distinguish four different demand categories for RH: Single and Multi Family Houses as well as existing and new buildings. In the model we assume that dwellings constructed after the year 2000 are new buildings. The model uses USD2000 as currency, and a 5% discount rate. One of the specific features of the MARKAL-CHRES model is that it includes a representation of a set of technologies which allow for energy savings. The idea behind those technologies is to take into account the reduction of energy demand which follows certain types of investment. For example, installing double-glazed windows increases insulation and therefore reduces heating demand. For a more detailed description of the technologies used in the MARKAL-CHRES model, see Schulz (2007).

2.3 Baseline calibration

Both models are calibrated to produce a common baseline. In GEMINI-E3, we use the projections from Energy Information Administration (2008) to estimate future prices for oil up to 2030 (70.5 USD_{2006}/bbl) and assume a constant increase of 2% up to 2050 so that oil price reaches 109.6 USD_{2006}/bbl. Based on various studies (Awerbuch and Sauter, 2006; Siliverstovs et al., 2005), we assume an indexation of gas prices to the price of oil at 0.75 (i.e. the price of gas increases by 7.5% when the oil price increases by 10%). For the MARKAL-CHRES model, we aligne the variation of energy prices, using the growth rates of energy prices in GEMINI-E3. Furthermore, population and economic estimates (e.g. GDP) together with construction estimations are used in order to estimate the Reference Energy Area (REA), i.e. the total useful surface of all heated rooms. The heating demands or useful energy used for heating (TJ/year) is equal to the Specific Room Heating Demand (MJ/m^2year) multiplied by REA (Mio m^2).The Swiss Federal Office of Energy provides estimates of the REA until 2035. Values until 2050 are extrapolated. Assuming a constant per capita energy demand for all other demand segments, we define them using the growth rate of the Swiss population. The Swiss population is expected to grow until 2030 at a level of approximately 7.4 million people and then slowly decrease to reach 7.25 in 2050. Finally, according to the projections by State Secretariat for Economic Affairs (2004), the annual average GDP growth rate is expected to be 1.2% from 2001 to 2020, and 0.6% from 2020 to 2050.

We use the baseline fuel mix from MARKAL-CHRES in GEMINI-E3 in order to align the emissions in the residential sector between the two models. The shares between the different energies are set to the shares of the fuel mix. Moreover, we define the technical progress in the residential energy nest so that the variations of the total residential energy use in GEMINI-E3 follows the same growth we observe in MARKAL-CHRES. Finally, we also define the growth of the technical progress in the private transport energy nest and of the general technical progress on the use of fossil fuels to 1.25% in order to have the total CO_2 emissions baseline decline by 13% between 2000 and 2035 as forecasted by Swiss Federal Office of Energy (2007).

With regard to total GHG emissions, our baseline scenario is in the average of studies published since the SRES (IPCC, 2007). The world GHG emissions reache approximately 72 $GtCO_2eq$ in 2050, which is also in line with the baseline emissions anticipated in OECD (2008). Our baseline assumes a great diversity in the regional evolution of GHG emissions (see figure 4). CHE and JAP emissions reduce by 24% in 2050 compared to 2001 levels. EUR and OEC see an increase in emissions of 9% and 21% whereas OEU and DCS have higher baseline emission growths and reach by 2050 113%, respectively 212%, of 2001 emission.

2.4 Coupling

Post-2012 policies should aim at strong abatement targets which could hopefully ensure a sustainable solution to the climate change issue. Global CGE models are well suited to analyze market based solutions to the problem, in particular when trying to globally equate marginal abatement cost through the implementation of carbon markets or world taxes. When it comes to strong domestic abatement efforts, which will be required in developed countries before the end of the century, CGE models do not precisely depict all technological option and therefore all abatement possibilities. In Switzerland, for instance, the residential sector accounts for a an important share of the total GHG emissions and seems to allow for important abatement possibilities at reasonable costs (see Sceia et al. (2008)). In general, coupling top-down with bottom-up models allows to benefit from the technological richness of the later without loosing the global economic picture (Böhringer, 1998; Böhringer and Rutherford, 2008). Therefore, in order to analyze thoroughly future Swiss climate policies within a global framework, we couple a CGE model, GEMINI-E3, with a Swiss residential energy model, MARKAL-CHRES.

2.4.1 Coupling method

We have further developed the coupling module that links GEMINI-E3 and MARKAL-CHRES. The coupling module researches the Swiss GHG tax in 2050 that allows to meet the policy objectives while ensuring that the energy use and the investments in the residential energy models is adequately taken into account in GEMINI-E3. The coupling method that we have implemented allows for setting simultaneously total and domestic emission targets for Switzerland as well as emissions certificates endowments in all regions. We consider that domestic targets have to be achieved by actual emissions reductions within the country, whereas total emissions target account for both domestic emissions and net trade of GHG certificates. In line with these definitions, when no domestic target is defined, the coupling procedures set a Swiss tax at a level that ensures that the tax revenue allows for purchasing enough certificates on the global carbon market in order to achieve the total emission target. If both domestic and total targets are defined, the coupling procedure ensures that the tax allows for achieving at least the domestic target and ensures that the tax revenue is sufficient to purchase enough emissions certificates to meet the total emissions target. In all cases, when the tax revenue exceeds the amount required to purchase the certificates, the difference is returned to households through a lump sum transfer.

Figure 2 presents the coupling schema. The GHG progressive tax vector, defined by the value of the tax in 2050, is the variable that allows to control both models. The residential fuel mix and the annualized investments over the whole time frame are the coupling variable ensuring that GEMINI-E3 calculates emissions and adjusts the residential investments in GEMINI-E3 on the basis of the MARKAL-CHRES simulations. The fuel shares are used as a proxy for the variation of the share parameters in the residential energy nest, which elasticity (σ_{hrese}) is set to 0, whereas the variation of the total fuel consumption and the variation of annualized investments are used, respectively, to update the values of the technical progress on energy and on construction in the residential nest, which is also transformed into a Leontief function ($\sigma_{hres} = 0$). Furthermore, total Swiss emissions and world price of GHG certificates in 2050 are the variables used for ensuring that the coupled models converge to the targets defined in the scenarios. Finally, the international policy scenarios are set exogenously, i.e. defining emissions certificates endowments.

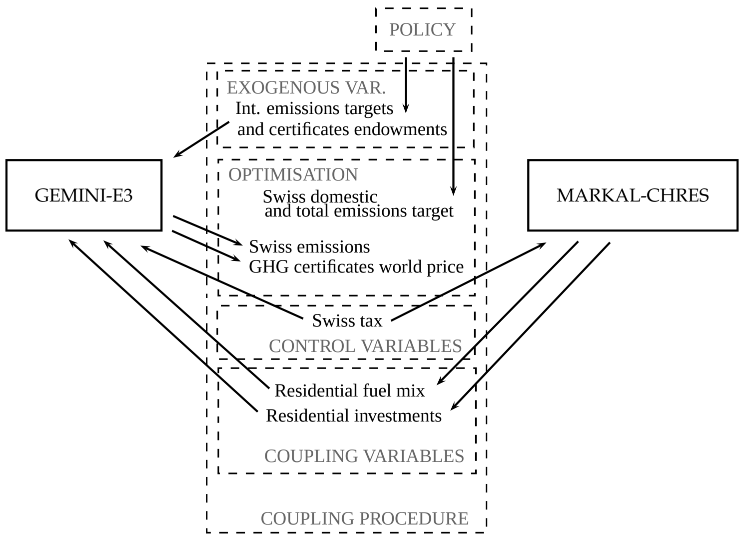

Figure 2: Coupling structure

A technical description of the coupling procedure is provided in algorithms 1 and 2 (see appendix A).

3 Policy scenarios

Climate change is a global issue which will only be solved through appropriate international agreements (Carraro and Siniscalco, 1993, 1998). It is also a complex issue in which environmental concerns interact with the economic, equity and development issues. Considering the later, the incentive to free ride can be high for some developing countries but it remains the responsibility of wealthier nations to take the lead and show the example. How much would it cost for Switzerland to take that leading role and to implement policies that might go beyond what international agreements target for the next commitment period?

3.1 International scenarios

In order to set a realistic international framework, we have defined 3 scenarios for international policies. We decided, following previous studies (e.g. Sceia et al. (2008); Vuuren et al. (2006)), to focus on policies targeting abatement of all GHG because this allows to lower abatement costs. Table 1 presents the different GHG emissions quotas in 2050 for all regions, with the exception of those from Switzerland which will be explained in details below. These emissions targets are implemented progressively from 2008 to 2050 for EUR and JAP, from 2012 to 2050 for OEC and OEU and from 2030 to 2050 for DCS. These emission targets are based on 2001 emissions levels except from those of DCS which are based on their 2030 baseline emissions. We assume that each region receives annually emissions certificates at the level of its annual target and is then free to trade them within the region as well as with other regions. The "high" scenario is inspired by the recommendations of the Energy Modeling Forum 22 (EMF, 2008) and adapted to the specific regional aggregation that we use in the model. The "mid" and "low"scenario consider alternatives where climate negotiations would lead to lower emission targets, in particular from the DCS.

Table 1: International emissions targets in 2050 (% of 2001 emissions)

Scenario	Low	Mid	High
EUR	50	50	50
OEU	10	20	30
JAP	50	50	50
OEC	30	40	50
DCS[a]	-[b]	0	25

[a] % of 2030 emissions
[b] baseline emissions

3.2 Swiss scenarios

In the long run, in order to avoid major climate change, each and every country will have to reduce its domestic emissions. From an equalitarian perspective, global emission will certainly have to be shared on a per capita basis. Taking this into account and considering population forecasts, purchasing emissions certificates does not help industrialized countries preparing to an inevitable change in their production and consumption patterns. With that in mind, we consider two kinds of emissions targets for Switzerland. The first is a domestic emission target that can only be achieved by actual domestic emissions reductions either in the production or in the consumption of goods. The second is a total emission target that takes into account not only the domestic abatement but also the purchase and sales of emission certificates.

In Switzerland, we impose a progressive domestic GHG tax, which grows linearly from 2008 onward and reaches it final value in 2050. The tax revenue collected by the application of the tax is used to purchase GHG emissions certificates to reach the total emission target and the leftover, if any, is redistributed to households through a lump sum transfer. Figure 3 shows the case where no minimal domestic emissions target is set and where the tax is set to allow for the purchase of GHG emissions certificates abroad ensuring a total abatement of 50%. The area ABCD represents the tax revenue and the area GBEF the purchase of certificates at a price p_W. The level of the tax is therefore set to equalize areas ABCD and GBEF, ensuring that the revenue collected is sufficient to purchase the GHG emission certificates.

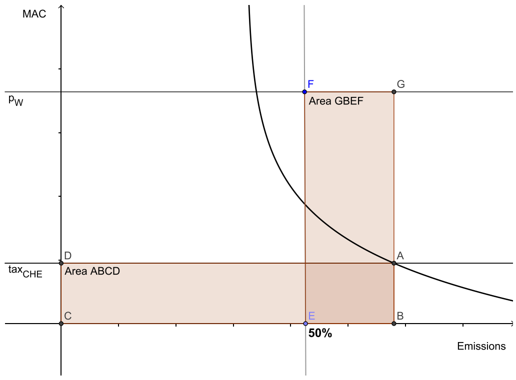

Figure 3: Tax revenue used to purchase GHG certificates, a 50% total abatement

We consider 4 scenarios with different objectives and therefore different total emission targets.

- First, the “50%” scenario is in line with the targets of most European countries. It aims at achieving a 50% reduction of emissions by 2050 compared to level of 2001.
- Secondly, the “sustainable” scenario aims at globally sustainable per-capita emissions of 1 tCO_2/cap by 2100. We consider, as simplifying assumption and to be in line with the time horizon of the model, that this translates in a 2 tCO_2/cap target by 2050. Considering that the population of Switzerland in 2050 is estimated at approximately 7 millions inhabitants, the emissions reduction should be of approximately 75% when compared to 2001 levels.
- Thirdly, the “neutral” scenario, which follows the climate neutrality idea, aims at a 100% reduction of GHG emissions.
- Fourthly, the “zero footprint” scenario takes into account the net emissions embedded in Swiss foreign trade. The net embedded emissions, mainly due to energy imports, represent almost 80% of total domestic emission (Jungbluth et al., 2007). Thus, this scenario aims at offsetting not only the domestic emissions but also those generated abroad to produce goods imported in Switzerland less the Swiss emissions resulting from the production of exported goods. With the simplifying hypothesis that that the embedded emissions remain constant, we consider that the abatement should reach 180% of 2001 emissions.

In all four scenarios, we set the Swiss tax such as the revenue of the tax is sufficient to purchase the emissions certificates required to offset the Swiss emissions up to the defined target.

Considering that Swiss marginal abatement costs are currently high when compared to world average, the implementation of the previous scenarios might not trigger important domestic abatement in the short run. In order to prepare the Swiss economy for future stringent emission reductions, a domestic reductions should be ensured in the forthcoming commitment period. With that in mind, we consider four additional scenarios similar to those described above but with the additional requirement of having a minimum domestic abatement of 50% compared to the emissions of 2001. We name those scenarios "50%+", "sustainable+", "neutral+" and "zero footprint+".

4 Results

In this section, we describe and compare the results of the simulation carried out for all the scenarios described earlier. We compare their environmental effectiveness and present their consequences on the economy, in particular on welfare. First, we focus on the different implications of the international scenarios, then on the impacts of all scenarios on the Swiss economy and finally we analyze the contribution of the Swiss residential sector to the overall abatement effort and the evolution of the sector from a technical perspective.

4.1 International framework

The three international scenarios we have defined have significantly different environmental and economic implications. From the perspective of GHG emission, in the "low" scenario, world emissions are still more than 80% higher than in 2001. In the "mid" scenario, the increase of emissions is reduced to 30%, whereas the "high" scenario caps the GHG emissions at 34 $GtCO_2eq$, only 2% higher than 2001 levels. Figure 4 presents the regional emissions profiles for the three scenarios. In all scenarios, DCS is the main provider of emissions certificates. The abundance of certificates in the first two scenarios, where DCS quotas are attributed according to the baseline emissions or stabilizing at 2030 levels, ensures a low price for CO_2. Nevertheless, in the "high" scenario, where DCS have to reduce their emissions as off 2030, the supply of certificates is significantly reduced and the price increases to almost 300 USD_{2001}/tCO_2eq. It is important to notice that, if we compare the emissions paths with the different IPCC scenarios (IPCC, 2007), even our "high" scenarios is not sufficiently restrictive to ensure a stabilization of GHG limiting the temperature increase to 2°C.

In order to asses the impact of the three scenario on the world economy, table 2 presents an aggregated welfare decomposition for the period 2008-2050. The welfare, i.e. the consumer surplus calculated on the basis of the CVI, is decomposed in its three components: the gains and losses of the terms of trade (GTT), the net receipt from permit sales and the deadweight loss of taxation. The values in the table represents the sum of the discounted values as a percentage of the sum of the discounted households final consumption. The discount rate is set at 5% but increasing or lowering it does not significantly affect the results.

Table 2: Welfare decomposition (in % of final households consumption)[a]

Scenarios	Region	WG[b]	GTT[c]	EC[d]	DWL[e]
Low	OEU	-0.28	0.16	-0.28	-0.16
	JAP	-0.03	-0.01	-0.01	-0.01
	EUR	-0.09	-0.03	-0.04	-0.03
	OEC	-0.08	-0.04	-0.03	-0.01
	PVD	0.13	0.07	0.08	-0.02
	World	0.00	-	-	0.00
Mid	OEU	-0.28	0.36	-0.65	-0.58
	JAP	-0.08	-0.04	-0.02	-0.02
	EUR	-0.24	-0.06	-0.10	-0.07
	OEC	-0.22	-0.10	-0.08	-0.04
	PVD	0.25	0.17	0.21	-0.13
	World	-0.04	-	-	-0.04
High	OEU	-3.77	-0.19	-1.31	-2.27
	JAP	-0.08	-0.01	-0.03	-0.05
	EUR	-0.45	-0.05	-0.28	-0.13
	OEC	-0.52	-0.15	-0.22	-0.15
	PVD	0.41	0.28	0.53	-0.41
	World	-0.23	-	-	-0.23

[a] Sum of discounted values as % of the sum of discounted final households consumption (2008-2050) - 5% discount rate

[b] Total welfare

[c] Gains and losses of the terms of trade

[d] Net revenue from the trade of GHG certificates

[e] Deadweight loss

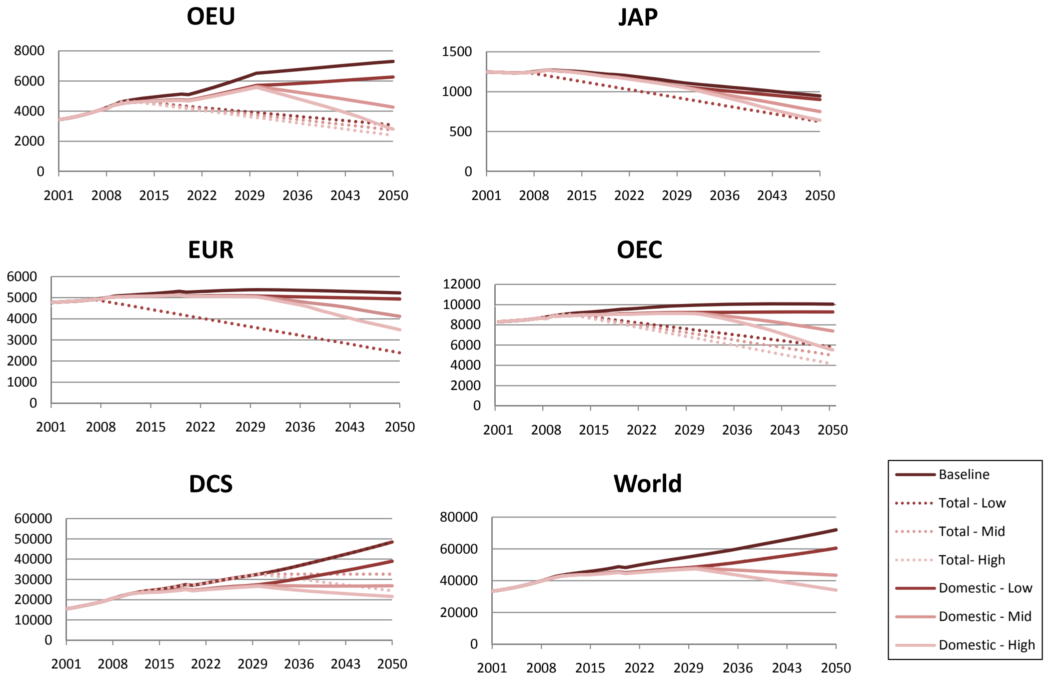

Figure 4: International GHG emissions ($MtCO_2eq$)

As in other studies (see OECD (2008)), we observe that OEU is the region most affected by climate policies. This is due to the fact that the main exports of this region are energy or energy related but also to the strong efforts they have to undertake in view of their high baseline emissions. Furthermore, they tend to have domestic oil prices below international levels, a framework favoring energy intensive industries, and are therefore more affected in a carbon-constrained world. In the three scenarios, DCS are the main beneficiaries in terms of consumer surplus. This is due to the revenue of the sales of certificates as well as the gains in the terms of trade. When looking at the deadweight loss of taxation, we realize that DCS are actually also affected, in particular in the high scenario. Concerning the other regions, JAP has limited losses in both consumer surplus and deadweight loss because in the baseline their emissions already reduced by almost 25%; a consequence of a slow GDP growth. EUR and OEC face similar impacts on total welfare with losses ranging from of 0.01% of aggregated total households consumption in the “low” scenario to 0.15% in the “high” scenario. In view of these results, it appears that even the “high” scenarios would be achievable at reasonable costs. We compare these results with those from Switzerland here after.

4.2 Swiss economy

Table 3 shows the key results for Switzerland in each scenario. In the international “high” scenario, the “sustainable”, “neutral” and “zero-footprint” already achieve the 50% domestic abatement prescribed in their equivalent “+” scenarios. As a consequence, the results of the "sustainable+", "neutral+" and "zero-footprint+" are identical to the non-"+" scenario and therefore not presented in the table.

Table 3: Summary results for Switzerland

Scenarios		Abatement in 2050[a]		Swiss	GHG	2008-2050[d]			
World	Switzerland	Domestic	Total	tax[b]	price[c]	WG	GTT	EC	DWL
Low	50%	-28	-50	1.2	3.8	-0.01	-0.01	-0.01	0.01
	sustainable	-28	-75	2.5	3.8	-0.02	-0.02	-0.02	0.01
	neutral	-28	-100	3.8	3.8	-0.02	-0.02	-0.02	0.02
	zero-footprint	-29	-180	8.2	3.9	-0.05	-0.02	-0.05	0.02
	50%+	-50	-50	102.4	3.8	0.21	0.29	0.00	-0.08
	sustainable+	-50	-75	102.4	3.8	0.20	0.28	-0.01	-0.08
	neutral+	-50	-100	102.4	3.8	0.19	0.28	-0.01	-0.08
	zero-footprint+	-50	-180	102.4	3.8	0.17	0.27	-0.04	-0.07
Mid	50%	-31	-50	9.7	34.6	-0.05	-0.03	-0.02	0.01
	sustainable	-33	-75	21.7	34.7	-0.05	-0.02	-0.04	0.00
	neutral	-40	-100	34.8	34.8	-0.03	0.03	-0.05	0.00
	zero-footprint	-50	-180	90.6	35.1	0.06	0.20	-0.11	-0.03
	50%+	-50	-50	102.4	34.6	0.18	0.26	0.00	-0.08
	sustainable+	-50	-75	102.1	34.7	0.16	0.25	-0.02	-0.07
	neutral+	-50	-100	101.9	34.7	0.14	0.24	-0.04	-0.06
	zero-footprint+	-50	-180	101.4	35.1	0.06	0.21	-0.11	-0.04
High	50%	-40	-50	50.7	289.2	0.07	0.11	-0.03	-0.01
	sustainable	-50	-75	143.7	289.8	0.12	0.30	-0.06	-0.12
	neutral	-54	-100	290.7	290.6	0.08	0.42	-0.13	-0.21
	zero-footprint	-63	-180	926.5	293.6	-0.25	0.88	-0.37	-0.75
	50%+	-50	-50	149.2	288.8	0.20	0.34	0.02	-0.15

[a] % of 2001 emissions
[b] Swiss tax in 2050 [USD_{2001}/tCO_2eq]
[c] World price of certificates in 2050 [USD_{2001}/tCO_2eq]
[d] Sum of discounted values as % of the sum of discounted final households consumption (2008-2050) - 5% discount rate

The results from Table 3 show that, in general, international climate policies have a strong influence on the effect of domestic GHG taxes. In the "low" and "mid" scenario, regardless of the implemented Swiss policy, the DWL caused by the climate policy is not larger than 0.08%. These costs are similar to those of other developed regions despite the fact that they face lower abatement targets. The exceptional case of OEU should be kept in mind and not compared with the other developed countries in view of the sensitivity of their economies to climate policies. In the high scenario, as it may be expected, there are stronger welfare effects. For instance, in the "zero footprint" scenario the DWL is 0.75% - not surprisingly as the level of domestic GHG tax in 2050 exceeds 900 USD_{2001}/tCO2eq. Despite of the increasing dead weight losses, total welfare effects tend to remain positive. The positive levels of households' surplus are mainly due to the fact that GTT offset the adverse effects of the DWL. This counter-intuitive result, already mentioned in previous studies (see, for instance, Babiker et al. (2004); Bernard et al. (2005); Goulder (1995)), can be explained by several factors. First, we know that for energy importing countries like Switzerland[4], the implementation of CO_2 abatement, induces a gain of terms of trade coming from the decrease of fossil fuels consumption (Bernard et al., 2005). Secondly, the implementation of international emission trading has ambiguous effects on welfare given its interaction with

[4] 100% of fossil fuels used in Switzerland are imported

the terms of trade (Babiker et al., 2004). Thirdly, pre-existing distortions modify the results that could be expected in a first best setting (Goulder, 1995) and this is why CGE models that take into account existing taxes are so useful under these circumstances.

Our results suggest that the options proposed for a future Swiss climate policy are likely to have modest economic impacts - considering that there are no restrictions for minimum levels of domestic abatement. For instance, regardless of the international scenario, when targeting a 50% abatement level (for 2050) and allowing for the purchase of GHG certificates, Switzerland's welfare is less affected than in other regions (e.g. a 0.05% welfare loss in the mid scenario against 0.08% suffered by Japan). This is mainly due to the fact that, similarly as in Japan, the Swiss emission baseline achieves a significant part of the abatement at no additional costs for the policies analyzed here - as it takes into account the current climate policies. Moreover, Switzerland has a limited impact on the global price of GHG emissions certificates and has technological options to reduce GHG in the residential sector. Consequently, it is more inclined to devise climate policies going beyond the agreements discussed in international fora. Furthermore, the welfare costs supported by Switzerland seem reasonable even for the more ambitious policies. In most scenarios, without taking developing countries into consideration, Switzerland is better off than other regions. Only in the "zero footprint" and "zero footprint+" scenarios, Japan has less welfare losses than Switzerland under some of the international abatement schemes.

We further observe that when there is mandatory minimum level of domestic abatement, the economic impacts of the climate policies analyzed are favorable for Switzerland. There are welfare gains for all policies but the "zero footprint+". For instance, achieving a 50% reduction of domestic emissions in an international environment aiming at moderate abatement (i.e. the "low" and "mid" scenarios), would require a GHG tax of approximately 102 USD/tCO_2eq. Despite the fact that this tax may seem important when compared to a tax that allows for collecting sufficient money to purchase certificates to achieve the same target, i.e. 1.2 USD/tCO_2eq, the gains in the terms of trade allow for a higher total welfare - as we have explained above.

The effects of the policies on the Swiss economy are more noticeable when we consider the high world scenario. The largest welfare loss is of 0.25% for the "zero footprint+" scenario - whether or not there is a restriction for domestic abatement. Furthermore, if international targets are more stringent, as it is the case in the "high" scenario, the tax that allows reducing domestically 50% of the emissions should reaches almost 150 USD/tCO_2eq. This 50% increase in the level of the tax, compared to the "low" and "mid" scenarios, is due to the strong decrease in energy demand worldwide which leads to an important reduction of energy prices. An increase in the GHG tax is therefore necessary in order to achieve the same abatement. Interestingly, when aiming at a 75% reduction, the domestic abatement is also of 50% but, due to a large transfer of capitals caused by the purchase of expensive GHG certificates, the economy contracts sufficiently to allow for a lower tax, i.e. 143 USD/tCO_2eq, to achieve the same domestic target. Figure 5 schematically represents the effect of a translation of the MAC curve due to the reduced economic activity. The areas BCEF and HCDG represent respectively the tax revenues and the purchase of certificates in value. The figure shows that the tax allowing for 50% of abatement can be higher than tax (tax') which revenue is used to purchase GHG certificates to reach a 75% total abatement due to the reduction of the activity. Both taxes achieve a domestic 50% abatement, crossing their respective MAC curves in points A and B. The same effect, but at a lower scale, can also be observed in the results of the "mid" scenario where the taxes allowing for a 50% domestic abatement decrease when the total abatement requirements increase.

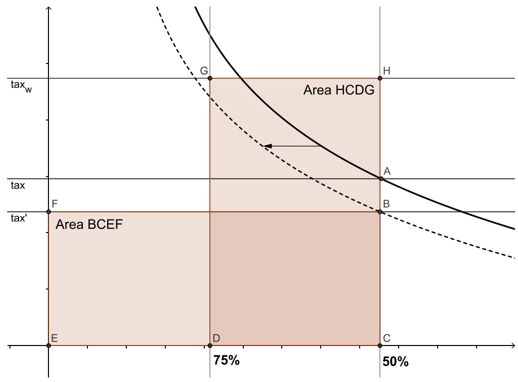

Figure 5: Translation of the MAC curve due to activity reduction

On the production side, there are no surprises for the two energy sectors active in Switzerland. On the one hand, Figure 6 shows that, in all scenarios, the "Petroleum products" sector, which is rather limited in size in Switzerland, is the major looser since its products are directly taxed. On the other and, the "electricity" sector benefits from the fact that the Swiss energy production is mainly produced from nuclear and hydro. It is important to note that the model assumes a continuity in the current electricity production patterns. Consequently, these results would change significantly if we would assume that nuclear power plants would be replaced by gas turbines.

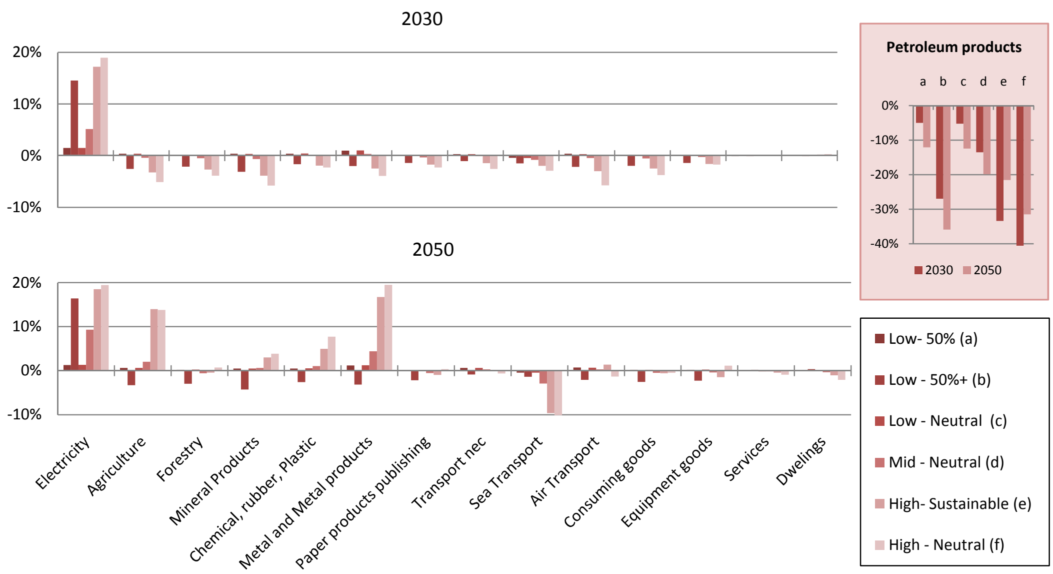

Figure 6: Sectoral production change due to the policy scenarios

The impact on the remaining sectors varies. Even strong climate policies have little impact on the "services" sector. Regarding road and rail transport (transport nec), the sector is not strongly affected even in the "high" scenario. In 2050, for those scenarios where the Swiss tax is inferior to the world price of certificates, the reduction of the demand for fossil fuels world wide drive the price down with directly benefits the sector in Switzerland. For the "neutral" scenario, in which the Swiss tax equals the price of certificates in 2050, the transport sector face an increase in energy prices of approximately 70% but nevertheless, in view of the low substitutability of transport to other inputs[5], the impact of the tax is low. If rail and road transport would have been separated sectors, we would certainly have witnessed a switch from road to rail, which, in Switzerland, uses almost exclusively electricity produced without fossil fuels.

The difference between the production patterns in 2030 and 2050 are explained by the non linear variation the price of the GHG certificates. Domestically, the GHG tax is defined as growing linearly from 2008 to 2050. Nevertheless, when it comes to the total emissions target, the price of certificates in highly influenced by the participation of DCS to the global abatement effort. In the "mid" and "high" scenarios, the price of GHG certificates starts to grow rapidly only as of 2030, when DCS start having a constraint on their emission. Figure7 show the difference in prices between the Swiss tax and the international price of certificates, in the "high-neutral" and "high-50%" scenarios. Therefore, the more GHG certificates need to be purchased, the more important are the transfers of money, which drive down the exchange rate, penalizing import and favoring exports.

As a consequence, some sectors come out surprisingly well in 2050, in particular in those scenarios where the price of GHG certificates is high. Among those, the "agriculture" and "chemical, rubber and plastic" sectors, two sectors know for their dependance on products derived from oil or oil itself, benefit from major changes in the trade patterns. In the "high - neutral" neutral scenario, the "chemical, rubber and plastic" sector sees an increase of exports overcoming the increase in imports and the agricultural imports drop almost 30%, thus stimulating the domestic production. Similarly, the Swiss "Mineral products" and "Metal and metal products" sectors also benefit strongly from the decrease in imports.

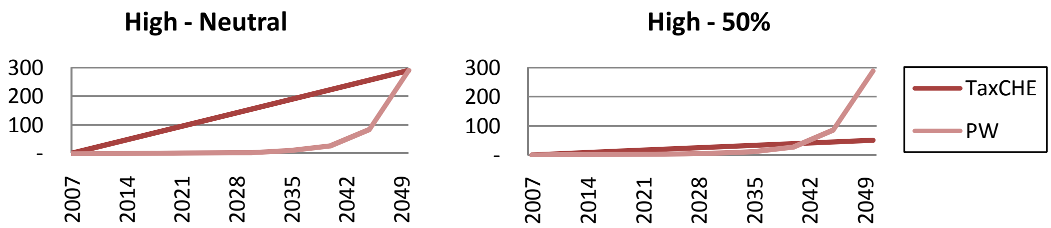

Figure 7: Swiss tax vs international price of certificates [UDS_{2001}/CO_2eq]

[5] the elasticity is set to 0.2

4.3 Swiss residential sector

4.3.1 Emissions

Figure 8 shows to what extent the residential sector can contribute to the abatement, by presenting how the emissions for the residential sector and from the rest of the economy evolve over time, as well as which part of the abatement is undertaken by the residential sector. The dashed lines show the targets of the total emissions. The MARKAL-CHRES, through its explicit modeling of technological options, shows that, without having to implement "backstop" technologies, a strong and natural switch to cleaner technologies takes place in case of high taxes. In order to avoid high costs in the future, households invest in cleaner technologies rapidly. The residential sector starts contributing significantly to the overall abatement when the GHG tax reaches around 30 USD/tCO_2eq (Mid - Neutral), and does the major part of it when the tax gets close to 100 USD/tCO_2eq (Low - 50%+)[6]. In the high scenarios, the residential sector stops emitting CO_2 as early as 2030, switching to technologies using electricity instead of fossil fuels.

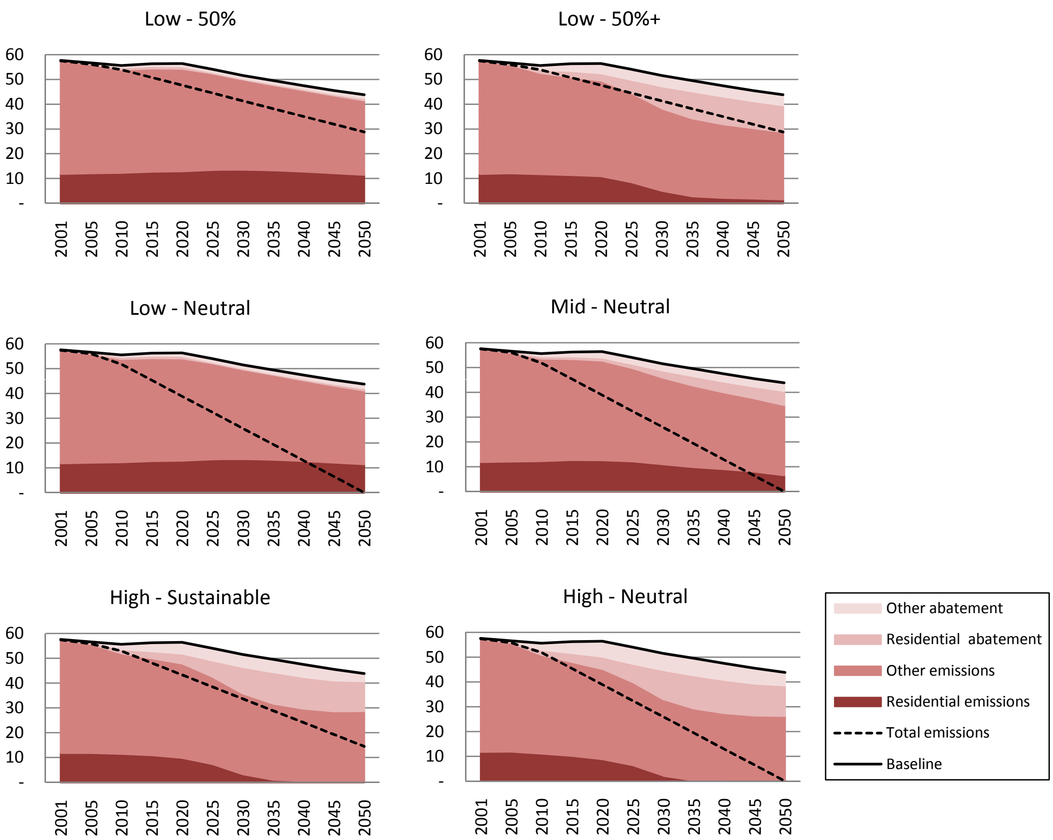

Figure 8: Contribution to the abatement of the residential sector (MtCO_2eq)

[6] We suspect that the private transportation, if modeled similarly to the residential sector, could provide additional abatement opportunities and, therefore, reduce the value of the tax

4.3.2 Energy consumption and technologies

For the evaluation of energy consumption and technologies we concentrate on the residential sector as a whole and more specifically on the residential heating sub-sector, which in 2000 accounted by far for the largest share of residential energy consumption. At the same time the residential heating sub-sector appears to offer substantial demand reduction possibilities in terms of available technological options and energy saving measures.

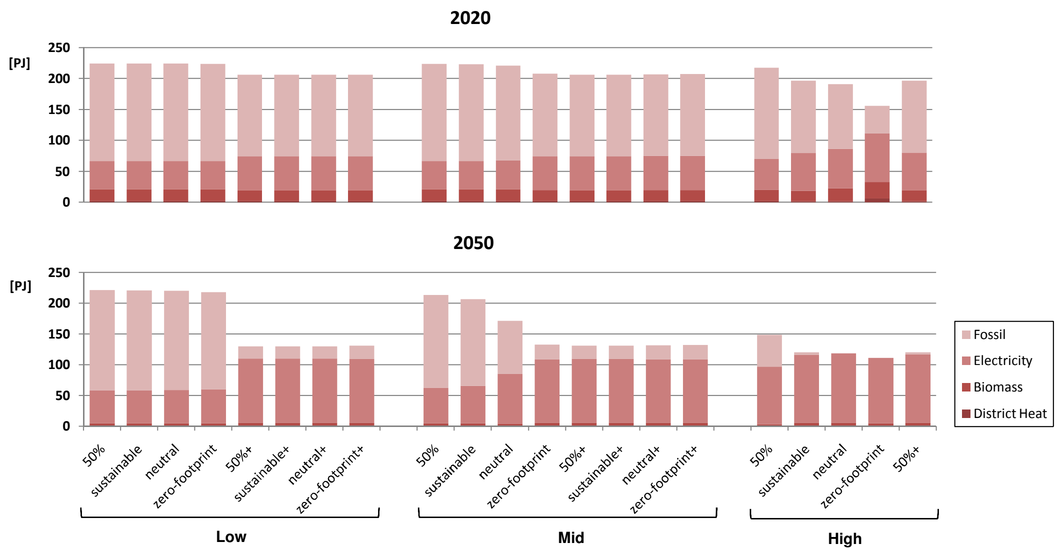

Figure 9: Fuel consumption in the residential sector

All scenarios examined here project a reduction, or at least a stabilization in residential fuel consumption from levels in 2000. For instance, according to IEA Statistics, residential energy consumption amounted to 234.6 PJ in 2000, while the highest observed value of all scenarios is 224.4 PJ in 2020 and 221.4 PJ in 2050. A similar trend is observed in the residential heating sub-sector, where even in the scenarios with the low emission reduction targets, energy consumption stabilizes around its year 2000 value of 165 PJ. Considering increases in residential floor area over the next 40 to 50 years, already this observation indicates that substantial improvements are likely to arise without stringent climate policy, even though further reductions in consumption are attainable when appropriate policy measures are implemented. However, these results also show that implementation of mild (low) world-wide emission targets does not achieve significant reductions in domestic fuel consumption when Switzerland is able to meet its emission reduction commitments through the purchase of tradable certificates. In this case, technological change is moderate, with technologies similar to the existing ones and that have slightly higher efficiencies but still consume the same type of fuel. Examples of these technologies include oil and natural gas room heating or combined room and water heating systems.

When low world-wide emissions targets are combined with a requirement to achieve emission reductions with domestic measures, we observe a significant impact on the Swiss residential sector. This impact is twofold. On the one hand such regulations reduce the

Table 4: Fuel consumption and energy savings for residential heating in PJ

Scenarios		All fuels[a]		Energy Savings[b]	
World	Switzerland	2020	2050	2020	2050
Low	50%	164.7	168.6	9.5	15.9
	sustainable	164.7	168.4	9.5	16.1
	neutral	164.7	167.9	9.5	16.3
	zero-footprint	164.4	165.2	9.8	17.1
	50%+	146.6	76.8	10.9	19.9
	sustainable+	146.6	76.8	10.9	19.9
	neutral+	146.6	76.8	10.9	19.9
	zero-footprint+	146.6	78.1	10.9	19.9
Mid	50%	164.4	160.7	9.8	17.1
	sustainable	163.8	154.3	10.4	18.1
	neutral	161.8	119.1	10.4	18.8
	zero-footprint	148.4	79.6	10.9	19.8
	50%+	146.6	78.1	10.9	19.9
	sustainable+	146.6	78.1	10.9	19.9
	neutral+	147.3	78.5	10.9	19.9
	zero-footprint+	147.9	79.0	10.9	19.9
High	50%	158.1	96.2	10.6	19.0
	sustainable	137.0	67.3	11.1	20.2
	neutral	131.0	65.2	11.3	20.9
	zero-footprint	95.7	57.9	13.4	23.5
	50%+	137.0	67.3	11.0	20.1

[a] Total energy used
[b] Useful energy saved

overall energy consumption. By 2020, residential energy consumption declines to 206 PJ and reduces further to about 130 PJ in 2050. A large share of this reduction occurs in the residential heating sub-sector, where energy consumption halves to about 78 PJ (relative to 2000 levels). On the other hand such regulations trigger fuel switching on a large scale. The consumption of fossil fuel reduces drastically to around 20 to 25 PJ in 2050, compared to around 160 PJ in the scenarios where Switzerland is able to meet its obligations through the purchase of certificates. This coincides with an increase in the consumption of electricity to more than 100 PJ. In the residential sector this change is triggered by switching from fossil heating installations to heat pumps in single and multi-family houses. New houses are constructed with heat pump and pellet heating installations. It is also worth reiterating that the residential sector still uses fossil fuels in all of the low scenarios. Although a minimum domestic abatement of 50% is required in Switzerland, the additional reductions required in the scenarios neutral+ and zero-footprint+ are achieved by purchasing emission certificates.

Only when high (stringent) world-wide emission targets are combined with strong domestic emission targets (corresponding to the neutral and zero-footprint scenarios), does the Swiss residential sector shift completely away from fossil fuels. Instead of purchasing emission certificates, additional electricity heat pumps are installed in single and multi-family houses to satisfy the heating demand, which due to their high efficiency lowers the final energy consumption. Additionally, by supporting and implementing enhanced energy-saving standards (i.e., improved insulation), the energy demand (useful energy) can be reduced by up to 23.4 PJ per year. Hence, high performance energy saving technologies contribute to a large share of the reduction in energy consumption. For example, better insulation of the housing stock, such as by using a double or triple-glazed window insulation with a thermal transmission coefficient of 1 W/m2k or less, is important in these scenarios. In addition to these energy saving options, expensive biomass and other renewable technologies (mainly pellet heating but also combined solar systems) also penetrate the domestic market to reduce emissions further.

This analysis of high emission targets indicates that the maximum energy reduction potential amounts to slightly more than 50% in the residential sector (compared to 2000 levels), for the set of technologies included. In the residential heating sub-sector, the energy reduction potential (combining energy saving and efficient heating technology) amounts to two-thirds of the energy consumed in the year 2000.

5 Conclusions

According to the results presented in this paper, Switzerland has the potential and the means to extend its climate policy beyond the 50% target currently under discussion for 2050. It could afford, independently of climate policies in other parts other parts of the world, to achieve a target of $2tCO_2eq/cap$ while ensuring at least 50% domestic abatement through the implementation of a domestic progressive GHG tax reaching 144 UDS/tCO_2eq in 2050. At first glance, ensuring domestic abatement through the implementation of a domestic tax may seem unreasonably expensive because of the current prices of CO_2. Nevertheless, our simulations show that through gains in the terms of trade, Switzerland would actually benefit in terms of total welfare from setting targets to domestic GHG emissions. Those gains would obviously be reduced when global emissions targets become tighter because an increased cost in the purchase of certificates. The tax would even have to be increased in case that the world target would go beyond our high scenario due to the drop in fossil energy prices that would follow the reduction in the demand.

When looking at the investments made in the residential sector, we can see that when economic agent have the certainty that fossil fuels will become more expensive in the future, they invest strategically and very rapidly in order to avoid excessive costs. Important technology options in this context include energy saving technologies (such as improved insulation), and efficient electric heat pumps, which reduce energy demand and facilitate a shift away from fossil fuels. In addition, for more stringent policies, biomass and renewables play an additional role. Regardless of this, this study shows that the technological alternatives to replace the fossil fuels in the residential sector exist, and those technologies become profitable when GHG taxes are implemented. Using our coupling procedure for other parts of the economy, e.g. private transportation, commercial buildings and industry, would bring additional technological option which are not taken into account in this study. Including further options is likely to provide additional flexibility in reducing emissions, thereby reducing abatement costs. In the framework of the coupling, the energy model somehow provides a similar feature as the implementation of an arbitrary backstop technology, but with a realistic technological description. This provides additional insights by identifying specific technologies and enhances the overall modeling framework. In our case, we see heat pumps being largely installed because of their high energy efficiency.

References

Le conseil fédéral veut réviser la loi sur le climat pour l'après 2012 et adopte les plans d'action de sa politique énergétique. Technical report, Federal Office for the Environment, February 2008. 2

S. Awerbuch and R. Sauter. Exploiting the oil-gdp effect to support renewables deployment. *Energy Policy*, 34(17):2805–2819, November 2006. 7

M. Babiker, J. Reilly, and L. Viguier. Is International Emission Trading Always Beneficial? *The Energy Journal*, 25(2):33–56, 2004. 16

A. Bernard and M. Vielle. Measuring the Welfare Cost of Climate Change Policies: A Comparative Assessment Based on the Computable General Equilibrium Model GEMINI-E3. *Environmental Modeling & Assessment*, 8(3):199–217, 2003. 5

A. Bernard and M. Vielle. GEMINI-E3, a General Equilibrium Model of International-National Interactions between Economy, Energy and the Environment. *Computational Management Science*, 5(3):173–206, May 2008. 4

A. Bernard, S. Paltsev, J.M. Reilly, M. Vielle, and L. Viguier. Russia's Role in the Kyoto Protocol. Report 98, MIT Joint Program on the Science and Policy of Global Change, Cambridge MA, June 2003. 4

A. Bernard, M. Vielle, and L. Viguier. Carbon tax and international emissions trading: A swiss perspective. In A. Haurie and L. Viguier, editors, *The Couplings of Climate and Economic Dynamics*, volume 22 of *Advances in Global Change Research*, pages 295–319. Kluwer Academic Publishers, 2005. 4, 16

C. Böhringer. The synthesis of bottom-up and top-down in energy policy modeling. *Energy Economics*, 20:233–248, 1998. 3, 8

C. Böhringer and T.F. Rutherford. Combining bottom-up and top-down. *Energy Economics*, 30:574–596, March 2008. 8

C. Carraro and D. Siniscalco. Strategies for the international protection of the environment. *Journal of Public Economics*, 52:309–28, 1993. 9

C. Carraro and D. Siniscalco. International environmental agreements: Incentives and political ecoomy. *European Economic Review*, 42:561–572, 1998. 9

B. V. Dimaranan, editor. *Global Trade, Assistance, and Production: The GTAP 6 Data Base*. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 2007. 4

L. Drouet, A. Haurie, M. Labriet, P. Thalmann, and L. Viguier. A coupled bottom-up/top-down model for GHG abatement scenarios in the housing sector of Switzerland. In R. Loulou, J.-P. Waaub, and G. Zaccour, editors, *Energy and Environment*, pages 27–61. Springer, New York (United States), 2005. 3

EMF. EMF 22 transition scenarios, July 2008. mimeo. 10

Energy Information Administration. *International Energy Outlook 2008*. EIA/DOE, Washington D.C., 2008. 7

ETHZ. Energy Strategy for ETH Zurich, February 2008. 2

M.C. Ferris and T.S. Munson. Complementarity problems in GAMS and the PATH solver. *Journal of Economic Dynamics and Control*, 24:165–188, 2000. 4

M.C. Ferris and J.S. Pang. *Complementarity and Variational Problems: State of the Art*. SIAM Publications, Philadelphia, Pennsylvania, 1997. 4

L. H. Goulder. Effects of carbon taxes in an economy with prior tax distortions: An intertemporal general equilibrium analysis. *Journal of Environmental Economics and Management*, 29(3):271–297, November 1995. 16

IMF. *Government Finance Statistics*. IMF, Washington, D.C. 20431, USA, 2004. 4

International Energy Agency. *Energy Balances for OECD Countries*. OECD/IEA, Paris, 2002a. 4

International Energy Agency. *Energy Balances for non-OECD Countries*. OECD/IEA, Paris, 2002b. 4

International Energy Agency. *Energy Prices & Taxes*. OECD/IEA, Paris, fourth quarter 2005. 4

IPCC, editor. *Climate Change 2007: Synthesis Report*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007. 2, 8, 12

N. Jungbluth, R. Steiner, and R. Frischknecht. Graue Treibhausgas-Emissionen der Schweiz 1990-2004. Erweiterte und aktualisierte Bilanz. Umwelt-Wissen Nr. UW-0711, Bundesamt für Umwelt, Bern, 2007. 150 S. 2, 11

A. Löschel and A. Soria. Impact of an increased use of renewable electricity: A quantitative assessment with a hybrid CGE model. In *9th IAEE European Energy Conference*, Firenze, 2007. 3

R. Loulou, G. Goldstein, and K. Noble. Documentation for the MARKAL family of models. Energy technology systems analysis programme, OECD/IEA, 2004. 6

A.S. Manne and R.G. Richels. *Buying greenhouse insurance: the economic costs of CO_2 emission limits*. The MIT Press, Cambridge, 1992. 3

A. Meyer. *Contraction & Convergence: The Global Solution to Climate Change*. Schumacher Briefings, 5, 2000. 2

C. Nathani, M. Wickart, R. Oleschak, and R. van Nieuwkoop. Estimation of a swiss input-output table for 2001. Technical report, ETH Zürich, 2006. 4

OECD. *National Accounts for OECD Countries*. OECD, Paris, 2005. 4

OECD. *Environmental Outlook to 2030*. OECD, 2008. 8, 12

OECD. *Revenue Statistics 1965-2002*. OECD, Paris, 2003. 4

W. Pizer, D. Burtraw, W. Harrington, R. Newell, J. Sanchirico, and M. Toman. General and Partial Equilibrium Modeling of Sectoral Policies to Address Climate Change in the United States. Technical report, Resources for the future, Washington, D.C., March 2003. 3

A. Sceia, L. Drouet, and M. Vielle. Transformation of the 2001 Swiss SAM from ETH Zürich to GEMINI-E3 format. Mimeo, March 2007. 4

A. Sceia, J.-C. Altamirano-Cabrera, L. Drouet, T.F. Schulz, and M. Vielle. Integrated assessment of Swiss GHG mitigation policies after 2012 - focus on the residential sector. *NCCR-Climate Working Papers*, 2008. 3, 8, 10

A. Schäfer and H. Jacoby. Experiments with a Hybrid CGE-MARKAL Model. *Energy Journal*, Special Issue: Hybrid modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down:171–177, 2006. 3

T. F. Schulz. *Intermediate steps toward the 2000 watt society in Switzerland : an energy-economic scenario analysis*. PhD thesis, ETH Zürich, 2007. 7

T. F. Schulz, S. Kypreos, L. Barreto, and A. Wokaun. Intermediate steps towards the 2000 w society in switzerland: An energy-economic scenario analysis. *Energy Policy*, Volume 36, Issue 4:Pages 1303–1317, 2008. 6

B. Siliverstovs, G. L'Hégaret, A. Neumann, and C. von Hirschhausen. International market integration for natural gas? a cointegration analysis of price in europe, north america and japan. *Energy Economics*, 27:603–615, 2005. 7

State Secretariat for Economic Affairs. Ökonomisches Wachstum Schweiz - Zukunftszenarien, 2004. 7

Swiss Federal Office of Energy. Perspectives énergétiques pour 2035 (tome 1) synthèse. Technical report, Département fédéral de l'environnement, des transports, de l'énergie et de la communication Office fédéral de l'énergie, 2007. 8

United States Environmental Protection Agency. *Global Mitigation of Non-CO2 Greenhouse Gases*. Office of Atmospheric Programs (6207J) EPA 430-R-06-005, Washington, DC 20460, June 2006. 4

M. Vielle and L. Viguier. On the climate change effects of high oil prices. *Energy Policy*, 35 (2):844–849, February 2007. 4

L. Viguier, M. Vielle, A. Haurie, and A. Bernard. A Two-level Computable Equilibrium Model to Assess the Strategic Allocation of Emission Allowances Within the European Union. *Computers & Operation Research*, 33(2):369–385, February 2006. 4

D. Van Vuuren, J. Weyant, and F. de la Chesnaye. Multi-gas Scenarios to Stabilize Radiative Forcing. *Energy Economics*, 28(1):102–120, January 2006. 10

I. Wing. The synthesis of bottom-up and top-down approaches to climate policy: Electric power technologies and the cost of limiting US co2 emissions. *Energy Policy*, 34:3847–3869, 2006. 3

A Coupling algorithms

The algorithms below use the the following nomenclature:

$\bar{e}$	Total target on Swiss emissions
$\bar{e_d}$	Minimal target on Swiss domestic emissions
t_{min}	Minimum value of the Swiss GHG tax
t_{max}	Maximum value of the Swiss GHG tax
fm	fuel mix
ai	Annualized investments
$M()$	run of MARKAL-CHRES
e	Swiss GHG emissions
$target$	Variable indicating which of the domestic or total target is binding
p_W	World price of GHG certificates
$G()$	run of GEMINI-E3
$crit_d$	Swiss domestic criteria
$crit$	Swiss total criteria
$criteria$	Overall criteria
tax	Swiss GHG tax
Δtax	Variation of the tax between two iterations

Algorithm 1: GMC-1.8 Coupling procedure without minimum domestic target

Input: Total target on Swiss emissions $\bar{e}$
Output: Swiss tax tax
$t_{min} = 0$; $t_{max} = 100$;
$(fm, ai) = M(t_{max})$;
$(e, p_W) = G(t_{max}, fm, ai)$;
$crit = e - e \cdot t_{max}/p_W - \bar{e}$;
while $crit > 0$ **do**
    $t_{min} = t_{max}$; $t_{max} = t_{max} + 100$;
    $(fm, ai) = M(t_{max})$;
    $(e, p_W) = G(t_{max}, fm, ai)$;
    $crit = e - e \cdot t_{max}/p_W - \bar{e}$;
end
$tax = t_{min} + (t_{max} - t_{min})/2$;
while $|crit| > 0.01$ *and* $|\Delta tax| > 0.001$ **do**
    $(fm, ai) = M(tax)$;
    $(e, p_W) = G(tax, fm, ai)$;
    $crit = e - e \cdot tax/p_W - \bar{e}$;
    if $crit < 0$ **then**
        $t_{max} = tax$
    else
        $t_{min} = tax$
    end
    $tax = t_{min} + (t_{max} - t_{min})/2$;
end

Algorithm 2: GMC-1.8 - Coupling procedure with minimum domestic target $\bar{e_d}$

Input: Total target on Swiss emissions $\bar{e}$, Minimal target on Swiss domestic emissions $\bar{e_d}$

Output: Swiss tax tax

$target = 0$; $t_{min} = 0$; $t_{max} = 100$;
$(fm, ai) = M(t_{max})$;
$(e, p_W) = G(t_{max}, fm, ai)$;
$crit_d = e - \bar{e_d}$; $crit = e - e \cdot t_{max}/p_W - \bar{e}$;
while $crit_d > 0$ *or* $crit > 0$ **do**
    $t_{min} = t_{max}$; $t_{max} = t_{max} + 100$;
    $(fm, ai) = M(t_{max})$;
    $(e, p_W) = G(t_{max}, fm, ai)$;
    $crit_d = e - \bar{e_d}$;
    $crit = e - e \cdot t_{max}/p_W - \bar{e}$;
    if $crit_d \leq 0$ *and* $crit > 0$ **then**
        $target = t$; $criteria = e - rev/p_W - \bar{e}$;
    else if $crit_d > 0$ *and* $crit \leq 0$ **then**
        $target = d$; $criteria = e - \bar{e_d}$;
    end
end
$tax = t_{min} + (t_{max} - t_{min})/2$;
while $target = 0$ **do**
    $(fm, ai) = M(tax)$;
    $(e, p_W) = G(tax, fm, ai)$;
    $crit_d = e - \bar{e_d}$;
    $crit = e - e \cdot tax/p_W - \bar{e}$;
    if $crit < 0$ **then** $t_{max} = tax$ **else** $t_{min} = tax$;
    $tax = t_{min} + (t_{max} - t_{min})/2$;
    if $crit_d \leq 0$ *and* $crit > 0$ **then**
        $target = t$; $criteria = e - rev/p_W - \bar{e}$;
    else if $crit_d > 0$ *and* $crit \leq 0$ **then**
        $target = d$; $criteria = e - \bar{e_d}$;
    end
end
while $|criteria| > 0.01$ *and* $|\Delta tax| > 0.001$ **do**
    $(fm, ai) = M(tax)$;
    $(e, p_W) = G(tax, fm, ai)$;
    if $target = t$ **then**
        $criteria = e - e \cdot tax/p_W - \bar{e}$;
    else
        $criteria = e - \bar{e_d}$;
    end
    if $criteria < 0$ **then** $t_{max} = tax$ **else** $t_{min} = tax$;
    $tax = t_{min} + (t_{max} - t_{min})/2$;
end

B Details on characteristics of the models

Table 5: Dimensions of the complete GEMINI-E3 Model

Countries or Regions		**Sectors/Products**
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	

Table 6: MARKAL-CHRES Demand segments

RC1	Cooling
RCD	Cloth Drying
RCW	Cloth Washing
RDW	Dish Washing
REA	Other Electric
RH1	Room-Heating Single-Family Houses (SFH) existing building
RH2	Room-Heating SFH new building
RH3	Room-Heating Multi-Family Houses (MFH) existing buildings
RH4	Room-Heating MFH new buildings
RHW	Hot Water
RK1	Cooking
RL1	Lighting
RRF	Refrigeration