

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

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Abstract

Switzerland, like 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 would not only put Switzerland in a leading position regarding climate change issues but also pave the way for realizing longer-term climate objectives.

Key words: Switzerland, Climate policy, Climate neutrality, Coupled CGE, Welfare economics
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 many important issues that will be discussed, countries will have to decide upon the level of abatement they can achieve and the extent to which they allow the use of flexibility mechanisms like global GHG emissions certificates markets. The decision to commit to an emission reduction target and whether or not to use flexibility mechanisms are influenced by the expected welfare costs of the policies and the environmental objectives of the country. With the aim of defining its future climate policy, Switzerland launched recently a consultation procedure on the revision of the CO₂ Law. In this paper, we analyze four ambitious emission targets that are currently discussed in this revision process.

First, we consider an abatement of 50% by 2050 with respect to the 2001 emissions level. This is a reference target for developed countries since it has been extensively discussed in the European Union.

Secondly, the sustainable approach that reflects the fact that the ultimate goal of post-Kyoto climate policies will be to stabilize greenhouse gases (GHG) emissions at sustainable levels. Recent studies (IPCC, 2007) state that GHG 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 (Meyer, 2000; ETHZ, 2008), GHG emissions per capita would have to be globally limited to 1 ton of CO₂ equivalent (tCO₂eq) per annum by 2100. Such a target would have important global repercussions. On the one hand, it implies strong emissions abatement by developed countries, where current levels of emissions per capita are much higher (e.g. 7.2 tCO₂eq/cap in Switzerland in 2004). On the other hand, for developing countries, it means that their development could not be based on the technologies that con-

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Preprint submitted to International Energy Workshop 2009

February 25, 2009

tributed to the development of industrialized countries.

Thirdly, the neutrality approach that advocates offsetting 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. Switzerland has already mentioned climate neutrality in the framework of the revision of the CO₂ tax, as a potential option for the future of Swiss climate policy (FOEN, 2008)¹. This neutrality could be mainly achieved by means of large purchases of CO₂ certificates.

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. The share of embodied emissions in the Swiss net trade represents about 80% of the domestic emissions (Jungbluth et al., 2007) relative to 2001. Going one step further and taking embodied emissions into account for setting emissions targets could revolutionize 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 mainly achieved through the purchase of GHG emissions certificates and the global price of the certificates is low, the country might not start the necessary upgrading of its infrastructures or see the expected changes in consumption patterns. Without a minimal domestic abatement, the four approaches mentioned 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 include the additional requirement to have a 50% reduction of domestic emissions by 2050 relative to 2001.

The objective of this paper is to assess the economic consequences of such policies on the Swiss economy, considering as illustrative example the residential sector. In order to achieve our objectives, we analyze jointly 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 assumed to be influenced solely by the emissions targets adopted by other regions. Therefore, we have considered three different international scenarios, in which the world would commit to achieve a low, medium or high level of emissions abatement. In each of them, the Swiss tax is used to achieve a domestic abatement target and to collect the revenue that would allow for the purchase of foreign GHG emissions certificates.

In this paper, we use a coupled top-down bottom-up model that allows for a precise technological specification of the Swiss residential sector, where there is a substantial potential for GHG emissions abatement², without losing 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, Manne and Richels (1992); Böhringer (1998); Pizer et al. (2003); Drouet et al. (2005); Schfer and Jacoby (2006); Löschel and Soria (2007); Wing (2006); Sceia et al. (2008)). We have nevertheless followed an approach relatively different from those used by these authors. In Pizer et al. (2003), Schfer 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. Our approach has been instead to link the models in the simulation phase. In Böhringer (1998) and Wing (2006), technology details have been directly incorporated into 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 to 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 current consultation procedure on the future of the Swiss CO₂ 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 a hybrid model where the residential sector is completely removed from the top-down model and 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.

¹In this paper we consider neutrality differently from the proposal by the Federal Office of the Environment, as we define it as 100% offsetting of all GHG emissions

²In 2005, the residential sector represented 22.3% of total GHG emissions

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 USD₂₀₀₁/tCO₂eq.

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 sectors³. We defined the regions as follows: Switzerland (CHE), European Union (EUR)⁴, other European and Euro-asian countries (OEU)⁵, 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 Pang, 1997; Ferris and Munson, 2000). 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, 2005, 2002a,b), the OECD (OECD, 2005, 2003) and the International Monetary Fund (IMF, 2004). For Switzerland, we used data from the 2001 input-output table devised at the Swiss Federal Institute of Technology (ETH) in Zürich (Nathani et al.,

³The complete GEMINI-E3 represents the world economy in 28 regions (including Switzerland) and 18 sectors (see table 5 in appendix C 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).

⁴refers to the European Union member states as of 2008

⁵includes other European countries, Russia and the rest of the Former Soviet Union excluding Baltic states

2006), which we transformed into the GEMINI-E3 format (Sceia et al., 2007). All the data on emissions and abatement costs for non CO₂ GHG come from the U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2006).

Previously, GEMINI-E3 has been used to study the strategic allocation of GHG emission allowances in the enlarged 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 costs of implementation of the Kyoto protocol in Switzerland with and without international emissions trading (Bernard et al., 2005), and assess the effects of an increase of oil prices on global 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. The σ^x refer to the elasticity parameter of each node. Plain numbers in the figure refer to economic sectors as presented in appendix C table 5, those in brackets refer to sectors appearing at various levels in the CES function and numbers in italics are the values of the elasticity parameters. In Switzerland, only petroleum products are used as inputs in the transportation energy nest.

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 domes-

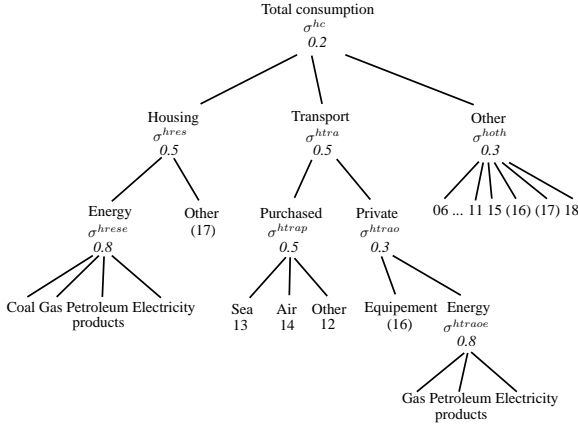


Figure 1: Structure of the households' nested CES utility function

tic 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 emissions. Measuring the costs of climate policies and comparing their efficiency can be done in various ways. A simple approach consists in analyzing the 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 compensating 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). In each region, the households' surplus or total welfare gains (WG_t) at each period t can therefore be expressed as

$$WG_t = \Delta R_t - CVI_t, \quad (1)$$

where ΔR is the variation of income, mainly due to transfers through international trade. The welfare gains vary greatly from the theoretical case of a closed 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

$$WG_t = DWL_t + GTT_t + EC_t, \quad (2)$$

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 follows,

$$GTT_t = \sum_i (X_{i,t}^0 \cdot \Delta P_{i,t}^X - M_{i,t}^0 \cdot \Delta P_{i,t}^M), \quad (3)$$

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

In order to present the total effect on welfare of a specific scenario, we represent the sum of the various discounted values as a percentage of the sum of the discounted households' final consumptions, 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 modeling 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, for instance, to analyze the Swiss 2000 Watt Society concept (Schulz et al., 2008). 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.

In the MARKAL-CHRES the energy demand in the base year (2000) 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 C table 6); each end-use demand being elastic to prices. The most important of these 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 USD₂₀₀₆ per barrel (bbl)) and assume a constant increase of 2% up to 2050 so that oil price reaches 109.6 USD₂₀₀₆/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 align the variation of energy prices, using the growth rates of prices observed 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/m²year) multiplied by REA (Mio m²). The Swiss Federal Office of Energy provides estimates of the REA until 2035. We extrapolate values un-

til 2050. 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 to a level of approximately 7.4 million people and then slowly decrease to reach 7.25 in 2050. Finally, according to the projections by the [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 follow 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 CO₂ 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 around the average of studies published since the SRES ([IPCC, 2007](#)). Global GHG emissions reach approximately 72 GtCO₂eq 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 decline 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 costs 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 options 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 gen-

eral, coupling top-down with bottom-up models allows to benefit from the technological richness of the latter without losing 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 determines the Swiss GHG tax in 2050 necessary to meet the policy objectives while ensuring that energy use and investments in the residential energy model are adequately taken into account in GEMINI-E3, as well as aligning energy prices between the models. The coupling method that we have implemented allows for setting simultaneously total and domestic emission targets for Switzerland as well as emissions certificate 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 as linearly increasing from zero in 2007 up to the value of the tax in 2050, is the variable that controls both models. The variation of energy prices in MARKAL-CHRES is aligned to the price variations observed in GEMINI-E3. The residential fuel mix and the annualized investments over the whole time frame are the coupling variables 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, with an elasticity of substitution (σ_{CHE}^{hres}) set to 0, whereas the variation of total fuel consumption and the variation of annualized

investments are used, respectively, to update the values of technical progress on energy (θ_{CHE}^{rese}) and on the residential consumption of services (θ_{CHE}^{res17}) in the residential nest, which is also transformed into a Leontief function ($\sigma_{CHE}^{hres} = 0$). Furthermore, total Swiss emissions and the 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 certificate endowments.

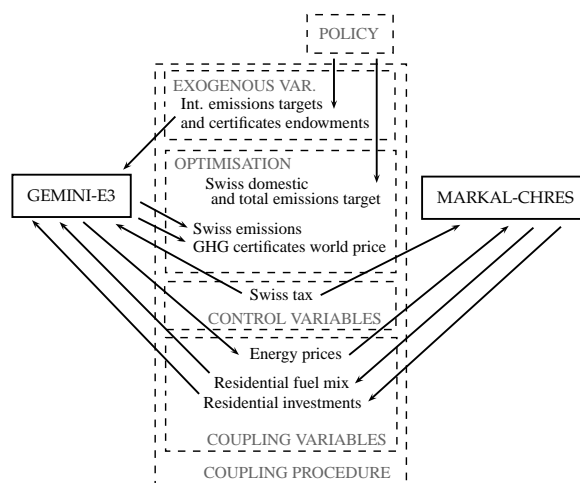


Figure 2: Coupling structure

The coupling module has 2 levels. The first level looks for the tax that will allow the emission target to be reached, while the second level ensures the alignment of energy prices with the fuel mix and the annualized investments for each tax that is tested. A technical description of the coupling procedure is provided in algorithms 2 and 3 (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 by 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. Vuuren et al. (2006); Sceaia et al. (2008)), to focus on policies targeting abatement of all GHGs because this results in lower abatement costs. Table 1 presents the different GHG emissions quotas in 2050 for all regions, with the exception of those for Switzerland which will be explained in detail 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 for 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” scenarios consider alternatives where climate negotiations would lead to lower emission targets, in particular for the DCS.

Table 1: International emissions targets in 2050 (% reduction relative to 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 should be shared on a per capita basis. Taking this into account and considering population forecasts, purchasing emissions certificates does not help industrialized countries prepare for 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 emissions 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 emissions target that takes into account not only the domestic abatement but also the purchase and sales of emissions certificates.

In Switzerland, we impose a progressive domestic GHG tax, which grows linearly from 2008 onward and reaches its final value in 2050. The revenue collected by the application of this tax is used to purchase GHG emissions certificates to reach the total emission target, with any leftover 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% (including compensation). 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 emissions certificates.

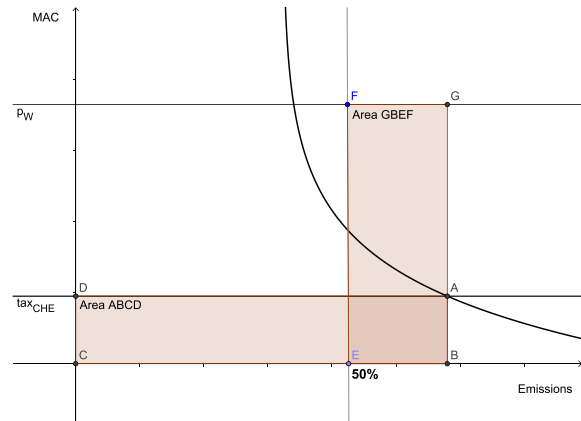


Figure 3: Tax revenue used to purchase GHG certificates for 50% total abatement

We consider 4 scenarios with different objectives and therefore different total emissions 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 the level of 2001.
- Secondly, the “sustainable” scenario, which aims at globally sustainable per-capita emissions of 1 tCO₂/cap by 2100. We consider, as simplifying assumption and to be in line with the time horizon of the model, that this translates to a 2 tCO₂/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 in 2050, largely through the purchase of emissions certificates.
- 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 the embedded emissions remain constant, we consider that the abatement should reach 180% of 2001 emissions in 2050.

In all four scenarios, we set the Swiss tax at a level such that its revenues are 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 significant domestic abatement in the short run. In order to prepare the Swiss economy for future stringent emissions reductions, a minimum of domestic reductions should be ensured. 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 simulations carried out for all the scenarios described earlier. We compare their environmental effectiveness (emissions reduction) and present their consequences for the economy, in particular for 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 abate-

ment 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 emissions, in the “low” scenario, world emissions are still more than 80% higher in 2050 than in 2001. In the “mid” scenario, the increase of emissions amounts to 30%, whereas the “high” scenario caps GHG emissions at 34 GtCO₂eq, 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 allocated according to the baseline emissions or stabilizing at 2030 levels, ensures a low price for CO₂. In contrast, in the “high” scenario, where DCS have to reduce their emissions by 25% relative to 2030, the supply of certificates is significantly reduced and their price increases to almost 300 USD₂₀₀₁/tCO₂eq. It is important to notice that, if we compare the emissions paths with the different IPCC scenarios (IPCC, 2007), even our “high” scenario is not sufficiently restrictive to ensure a stabilization of GHG concentrations limiting the temperature increase to 2°C.

Table 2 presents an aggregated welfare decomposition for the period 2008-2050 and it shows the impact of the three scenarios on the world economy. The welfare, i.e. the consumer surplus calculated on the basis of the CVI, is decomposed into 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 (see equation 2). The values in the table represent the sum of the discounted values as a percentage of the sum of the discounted households’ final consumptions. The discount rate is set at 5% but we find that increasing or lowering it does not change qualitatively the results.

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, and 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 therefore, they are 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 from the sale of certificates as well as the gains in the terms

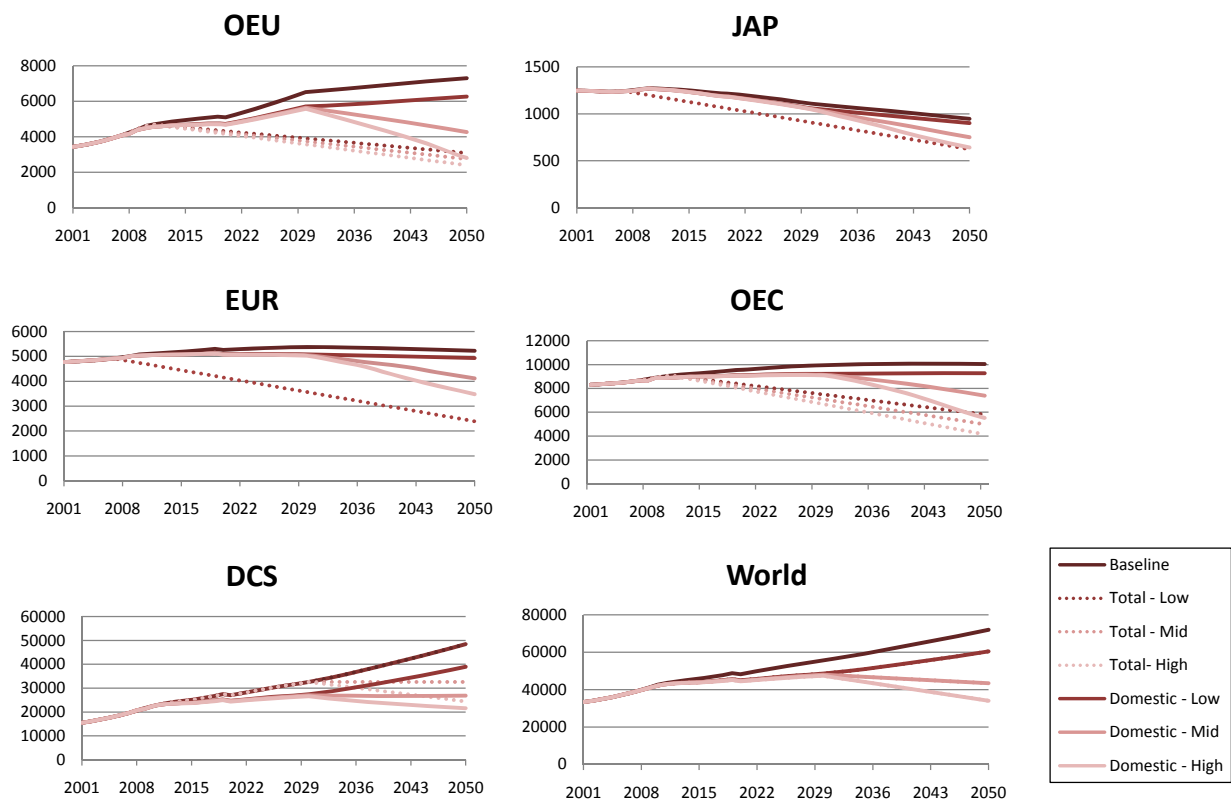


Figure 4: International GHG emissions (MtCO₂eq)

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 decline by almost 25%; a consequence of slow GDP growth. EUR and OEC face similar deadweight losses, ranging from of 0.01% of aggregated total households consumption in the “low” scenario to 0.10% 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 for Switzerland in the next section.

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” cases 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-“+” scenarios and are therefore not presented in the table.

The results in 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 0.07%. 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 0.73% - not surprisingly as the level of domestic GHG tax in 2050 exceeds 900 USD₂₀₀₁/tCO₂eq. Despite 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, Bernard et al. (2005); Babiker et al. (2004); Goulder (1995)), can be explained by several factors. First, we know

Table 3: Summary results for Switzerland

World	Scenarios	Abatement in 2050 ^a		Swiss tax ^b	GHG price ^c	2008-2050 ^d			
		Domestic	Total			WG	GTT	EC	DWL
Low	50%	-28	-50	1.2	3.8	0.02	-0.01	-0.01	0.03
	sustainable	-28	-75	2.5	3.8	0.01	-0.01	-0.01	0.04
	neutral	-28	-100	3.8	3.8	0.01	-0.01	-0.02	0.04
	zero-footprint	-30	-180	8.3	3.9	-0.01	-0.01	-0.05	0.04
	50%+	-50	-50	103.3	3.8	0.22	0.29	0.00	-0.07
	sustainable+	-50	-75	103.2	3.8	0.21	0.29	-0.01	-0.07
	neutral+	-50	-100	103.2	3.8	0.20	0.28	-0.01	-0.07
	zero-footprint+	-50	-180	103.1	3.8	0.17	0.27	-0.04	-0.06
Mid	50%	-32	-50	9.4	34.6	0.00	-0.02	-0.02	0.03
	sustainable	-36	-75	21.0	34.7	0.01	0.02	-0.03	0.02
	neutral	-40	-100	34.8	34.8	0.01	0.05	-0.05	0.02
	zero-footprint	-50	-180	90.6	35.1	0.06	0.20	-0.11	-0.03
	50%+	-50	-50	101.0	34.6	0.19	0.26	0.00	-0.07
	sustainable+	-50	-75	100.8	34.6	0.17	0.25	-0.02	-0.07
	neutral+	-50	-100	100.7	34.7	0.14	0.24	-0.04	-0.06
	zero-footprint+	-50	-180	100.0	35.1	0.07	0.21	-0.11	-0.03
High	50%	-35	-50	67.5	289.4	0.10	0.15	-0.03	-0.02
	sustainable	-50	-75	144.2	289.8	0.12	0.30	-0.07	-0.12
	neutral	-54	-100	290.7	290.6	0.10	0.43	-0.13	-0.20
	zero-footprint	-63	-180	926.5	293.6	-0.23	0.88	-0.37	-0.73
	50%+	-50	-50	156.7	288.8	0.21	0.35	0.02	-0.15

^a % of 2001 emissions

^b Swiss tax in 2050 [USD₂₀₀₁/tCO₂eq]

^c World price of certificates in 2050 [USD₂₀₀₁/tCO₂eq]

^d Sum of discounted values as % of the sum of discounted final households consumption (2008-2050) - 5% discount rate

that for energy importing countries like Switzerland⁶, the implementation of CO₂ 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 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. no welfare loss in the mid scenario against 0.06% suffered by Japan). This is mainly due to the fact that, similarly as in Japan, the Swiss emissions 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

⁶100% of fossil fuels used in Switzerland are imported

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

Scenarios	Region	WG ^b	GTT ^c	EC ^d	DWL ^e
Low	OEU	-0.24	0.13	-0.24	-0.13
	JAP	-0.03	-0.01	-0.01	-0.01
	EUR	-0.08	-0.02	-0.03	-0.02
	OEC	-0.07	-0.03	-0.02	-0.01
	PVD	0.11	0.06	0.07	-0.02
	World	0.00	-	-	0.00
Mid	OEU	-0.24	0.28	-0.51	-0.45
	JAP	-0.06	-0.03	-0.02	-0.02
	EUR	-0.18	-0.05	-0.08	-0.05
	OEC	-0.17	-0.08	-0.06	-0.03
	PVD	0.21	0.14	0.17	-0.10
	World	-0.03	-	-	-0.03
High	OEU	-2.72	-0.10	-1.00	-1.63
	JAP	-0.06	-0.01	-0.02	-0.03
	EUR	-0.33	-0.04	-0.20	-0.09
	OEC	-0.38	-0.12	-0.16	-0.10
	PVD	0.32	0.22	0.41	-0.30
	World	-0.16	-	-	-0.16

^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

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 does Japan suffer smaller 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 in all scenarios with the exception of 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 100 USD/tCO₂eq. Despite the fact that this tax rate may seem high when compared to the tax required to collect sufficient revenue to purchase certificates corresponding to the same target, i.e. 1.2 USD/tCO₂eq, the gains in the

terms of trade resulting from the higher tax 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 0.23% for the “zero footprint” and “zero footprint+” scenarios. 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 reach more than 150 USD/tCO₂eq. 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 a significant 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 under the “high” scenario, the level of domestic abatement is also 50%, but due to a large transfer of capital caused by the purchase of expensive GHG certificates, the economy contracts sufficiently to allow for a lower tax, i.e. 144 USD/tCO₂eq, 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 the tax (tax') whose 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.

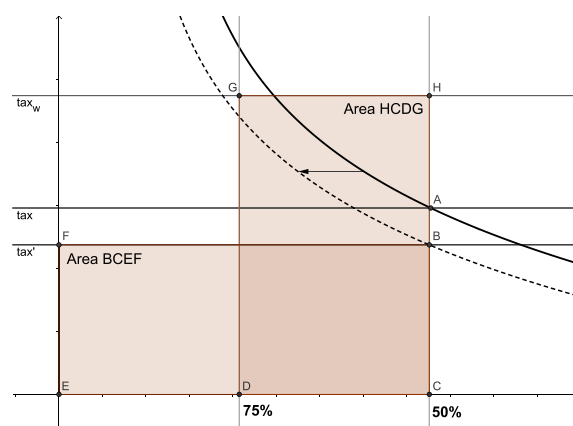


Figure 5: Translation of the MAC curve due to activity reduction

On the production side, there are no surprises for the two energy sectors active in Switzerland. Figure 6 shows that, on the one hand, the “Petroleum products” sector, which is rather limited in size in Switzerland, is the major loser in all scenarios since its products are directly taxed. On the other hand, 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.

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 lower than the world price of certificates, the reduction of the demand for fossil fuels world wide drives their price down, which directly benefits this sector in Switzerland. For the “neutral” scenario, in which the Swiss tax equals the price of certificates in 2050, the transport sector faces an increase in energy prices of approximately 70% but nevertheless, in view of the low substitutability of transport to other inputs⁷, the impact of the tax is low. If rail and road transport were separated sectors, we would certainly observe 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 in 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 is highly influenced by the participation of DCS in 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 are required to constrain their emissions. Figure 7 shows 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 drives down the exchange rate, penalizing imports 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 known for their dependence on products derived from oil or oil itself, benefit from major changes in the trade patterns. In the “high - 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 domestic production. Similarly, the Swiss “Mineral products” and “Metal and metal products” sectors also benefit strongly from the decrease in imports.

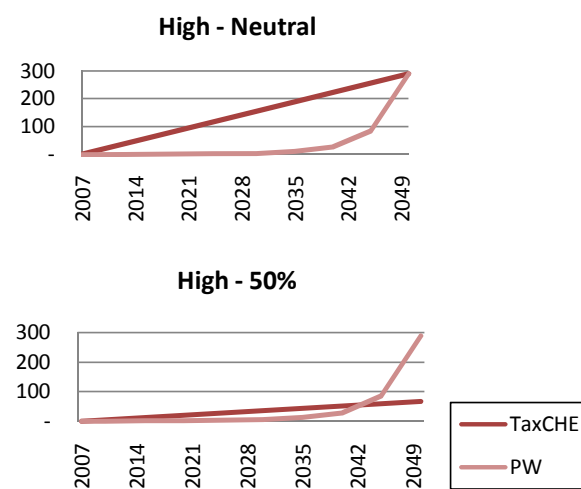


Figure 7: Swiss tax vs international price of certificates [USD₂₀₀₁/CO₂eq]

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 of the residential sector and of the rest of the economy evolve over time, as well as what share of the abatement is undertaken by the residential sector. The dashed lines show the targets of the total emissions, i.e. compensation being deducted. The modeling with MARKAL-CHRES, with its explicit representation 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 35 USD/tCO₂eq (Mid - Neutral), and does the major part of it when the tax gets close to 100 USD/tCO₂eq

⁷the elasticity is set to 0.2

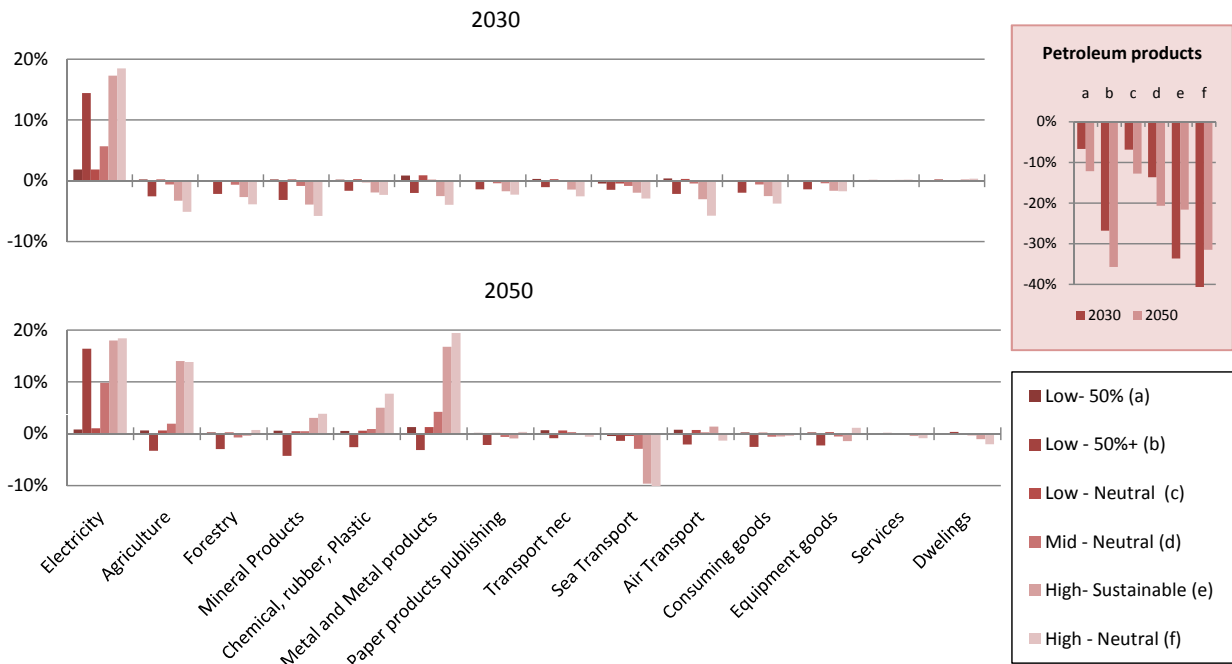


Figure 6: Sectoral production change due to the policy scenarios

(Low - 50%+)⁸. In the high scenarios, the residential sector stops emitting CO₂ as early as 2030, switching to technologies using electricity instead of fossil fuels.

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.

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 petajoules (PJ) in 2000, while the highest observed value of all scenarios is 224.4 PJ in 2020 and 225.9 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

⁸We suspect that private transportation, if modeled similarly to the residential sector, could provide additional abatement opportunities and, therefore, reduce the needed tax

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 and fuels similar those used today (but with slightly higher efficiencies) continuing to be the main options. 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 50% of the emission reductions domestically (“+”), we observe a significant impact on the Swiss residential sector. This impact is twofold. On the one hand such regulations reduce the overall energy consumption by promoting the adoption of energy-saving technologies, such as insulation. By 2020, residential energy consumption declines to 208 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

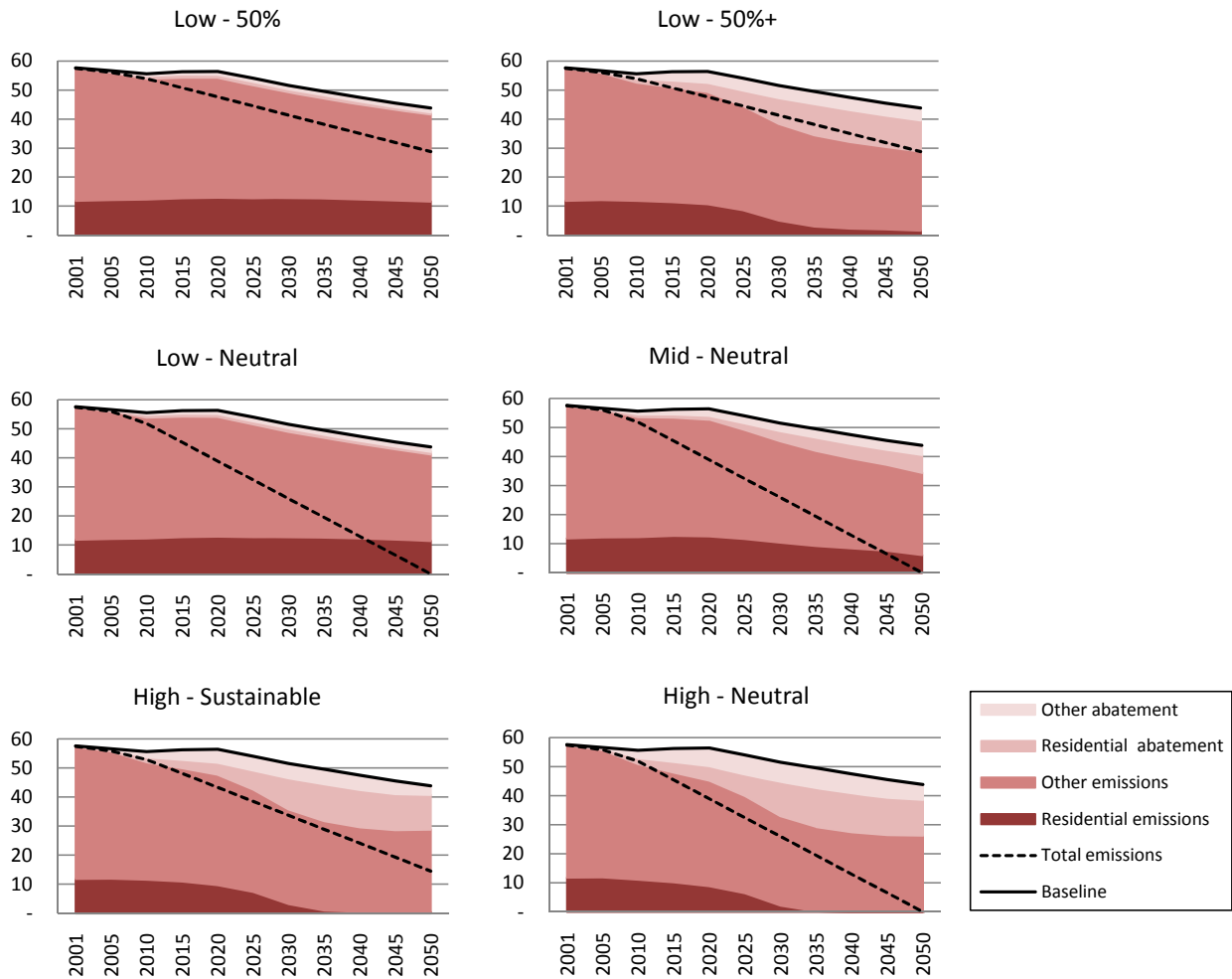


Figure 8: Contribution to the abatement of the residential sector [MtCO₂eq]

77 PJ (relative to 2000 levels). On the other hand such regulations also trigger fuel switching on a large scale. The consumption of fossil fuel diminishes drastically to around 20 to 25 PJ in 2050, compared to around 160 PJ in the scenarios where Switzerland is able to meet the targets 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 equipment to heat pumps in single and multi-family houses. New houses are constructed with heat pump and wood pellet heating equipment. 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 certifi-

cates.

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 electric 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 23.5 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

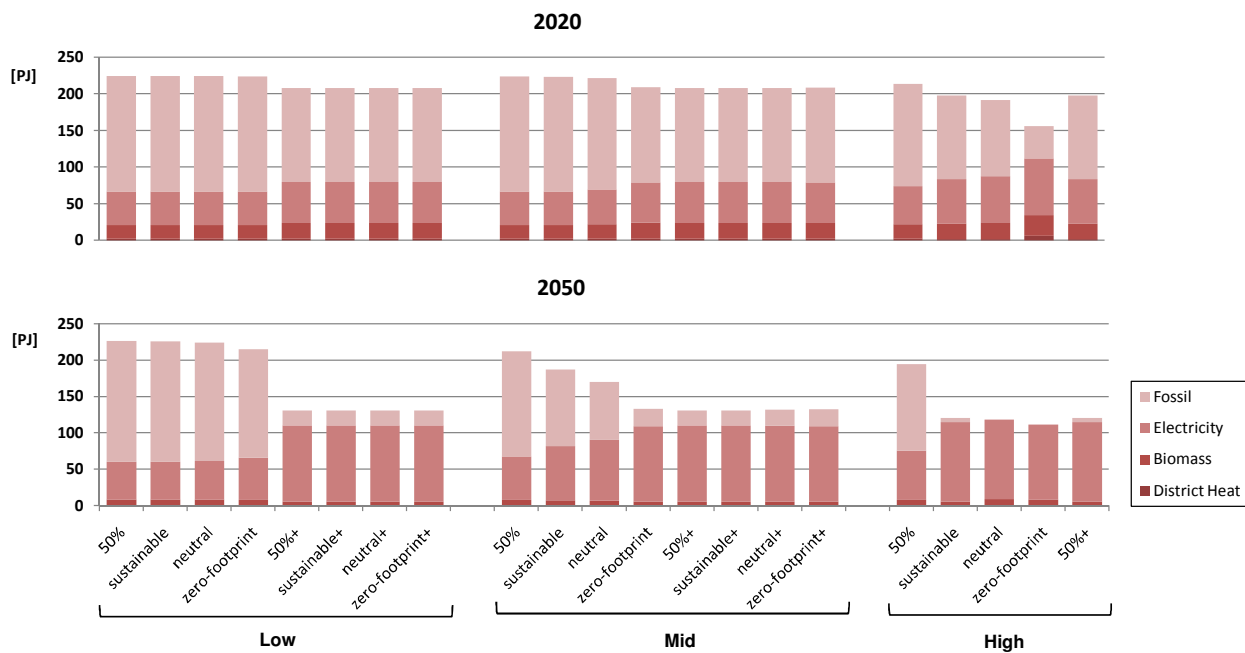


Figure 9: Fuel consumption in the residential sector

or triple-glazed window insulation with a thermal transmission coefficient of $1 \text{ W/m}^2\text{K}^9$ 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 reduction 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 of the world, to achieve a target of $2\text{tCO}_2\text{eq/cap}$ while ensuring at least 50% domestic abatement through the implementation of a domestic progressive GHG tax reaching 144

⁹watt per square meter-kelvin

$\text{USD}_{2001}/\text{tCO}_2\text{eq}$ 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 due to higher prices for international emissions 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 demand.

When looking at the investments made in the residential sector, we can see that when economic agents have the certainty that fossil fuels will become more expensive in the future, they should 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. This study shows that the technological alternatives to replace fossil fuels in the residential sector exist, and those technologies become profitable when GHG taxes are implemented. Using our

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	172.5	9.5	16.1	
	sustainable	164.7	172.2	9.5	16.5	
	neutral	164.7	170.3	9.5	16.5	
	zero-footprint	164.4	161.2	9.8	17.3	
	50%+	147.7	77.2	10.8	19.6	
	sustainable+	147.7	77.2	10.8	19.6	
	neutral+	147.7	77.2	10.8	19.6	
	zero-footprint+	147.7	77.2	10.8	19.6	
	Mid	50%	164.4	158.3	9.8	17.3
		sustainable	163.9	133.5	10.3	18.0
neutral		162.0	116.6	10.3	18.8	
zero-footprint		148.7	79.6	10.8	19.6	
50%+		147.7	77.2	10.8	19.6	
sustainable+		147.7	77.2	10.8	19.6	
neutral+		147.7	78.5	10.8	19.6	
zero-footprint+		148.2	78.9	10.8	19.6	
High		50%	153.8	126.4	10.7	18.9
		sustainable	137.5	67.2	11.1	20.2
	neutral	131.3	65.1	11.3	20.9	
	zero-footprint	95.8	57.9	13.4	23.5	
	50%+	137.3	67.2	11.2	20.3	

^a Total energy used

^b Useful energy saved

coupling procedure for other parts of the economy, e.g. private transportation, commercial buildings and industry, would bring additional technological options which are not taken into account in this study. These options would provide additional flexibility in reducing emissions, thereby reducing abatement costs. In the framework of 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.

Acknowledgements

This work has been undertaken with the support of the NSF-NCCR climate grant. We also would like to thank Philippe Thalmann, Hal Turton and Thomas Rutherford for their helpful comments as well as Laurent Drouet for his continuous support.

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
fm_b	baseline fuel mix
ai_b	baseline annualized investments
PE	energy prices
$M()$	run of MARKAL-CHRES
e	Swiss GHG emissions in the target year
$target$	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
$crit_{PE}$	energy prices criteria
$crit$	Swiss total criteria
$criteria$	overall criteria
tax	Swiss GHG tax
Δtax	variation of the tax between two iterations
ΔPE	variation of the prices of energies between two iterations

Algorithm 1: Procedure - RunMG

$(fm, ai) = M(t_{max}, PE);$
 $(e, p_W, PE) = G(t_{max}, fm, ai);$
 $crit_{PE} = \sum_{ij} |\Delta PE_{ij}|$
if $crit_{PE} > 0.01$ **then** call RunMG;
 $crit = e - e \cdot t_{max} / p_W - \bar{e};$
 $crit_d = e - \bar{e}_d;$

Algorithm 2: GMC-2.0 Coupling procedure without minimum domestic target

Input: Total target on Swiss emissions \bar{e}

Output: Swiss tax tax

$t_{min} = 0; t_{max} = 100;$

$(e, p_W, PE) = G(t_{min}, fm_b, ai_b);$

$tax = t_{max}$

call RunMG;

while $crit > 0$ **do**

$t_{min} = t_{max}; t_{max} = t_{max} + 100;$

 call RunMG;

end

$tax = t_{min} + (t_{max} - t_{min})/2;$

while $|crit| > 0.01$ **and** $|\Delta tax| > 0.001$ **do**

 call RunMG;

if $crit < 0$ **then**

$t_{max} = tax$

else

$t_{min} = tax$

end

$tax = t_{min} + (t_{max} - t_{min})/2;$

end

Algorithm 3: GMC-2.0 - 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

$target = 0; t_{min} = 0; t_{max} = 100;$

call RunMG;

while $crit_d > 0$ or $crit > 0$ **do**

$t_{min} = t_{max}; t_{max} = t_{max} + 100;$

 call RunMG;

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**

 call RunMG;

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**

 call RunMG;

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. Equations in the Residential nest

The residential part of the households consumption is calculated with the equations below where r refer to regions and t to the time period. λ , α and σ are respectively the scale, share and elasticity parameters of the CES functions.

The consumption of the residential aggregated good ($HCRES$) is calculated as:

$$HCRES_r \cdot \theta_r^{res t} = HCT_r \cdot \lambda_r^{hct} \cdot \alpha_r^{res} \cdot \left[\frac{PCT_r}{PCRES_r \cdot \lambda_r^{hct} \cdot \theta_r^{res t}} \right]^{\sigma_r^{hct}}, \quad (4)$$

where θ_r^{res} the technical progress of the residential nest, HCT is the total aggregated consumption, PCT the price of the aggregated consumption and $PCRES$ the price of the residential aggregated good.

The consumption of the residential aggregated energy good ($HCRES E$) is calculated as:

$$HCRES E_r \cdot \theta_r^{rese t} = HCRES_r \cdot \lambda_r^{hcrses} \cdot \alpha_r^{rese} \cdot \left[\frac{PCRES_r}{PCRES E_r \cdot \lambda_r^{hcrses} \cdot \theta_r^{rese t}} \right]^{\sigma_r^{hcrses}}, \quad (5)$$

where θ_r^{rese} the technical progress of the residential energy nest and $PCRES E$ is the price of residential aggregated energy good.

The residential consumption of services ($HC_{17,r}^{res}$) is calculated as:

$$HC_{17,r}^{res} \cdot \theta_r^{res17 t} = HCRES_r \cdot \lambda_r^{hcrses} \cdot (1 - \alpha_r^{rese}) \cdot \left[\frac{PCRES_r}{PC_{17,r} \cdot \lambda_r^{hcrses} \cdot \theta_r^{res17 t}} \right]^{\sigma_r^{hcrses}}, \quad (6)$$

where θ_r^{res17} the technical progress of the residential consumption of services and $PC_{17,r}$ is the price of the residential consumption of services.

The residential consumption of energies ($HC_{i,r}^{res}$) is calculated as:

$$HC_{i,r}^{res} = HCRES E_r \cdot \lambda_r^{hcrses} \cdot \alpha_{i,r}^{rese} \cdot \left[\frac{PCRES E_r}{PC_{i,r} \cdot \lambda_r^{hcrses}} \right]^{\sigma_r^{hcrses}}, \quad \forall i = 1, \dots, 5, \quad (7)$$

where PC_i the price of consumption goods i and $\sum_i \alpha_{i,r}^{rese} = 1$.

Furthermore, the residential nest accounts for only a part of the consumption of energy goods as well as services. In order to have the total final consumption in those sectors, we use the following formulas:

$$HC_{i,r} = HC_{i,r}^{res} + HC_{i,r}^{tra}, \quad \forall i = 1, \dots, 5, \quad (8)$$

$$HC_{17,r} = HC_{17,r}^{res} + HC_{17,r}^{oth}. \quad (9)$$

Finally, the prices of the aggregated goods ($HCRES$ and $HCRES E$) are calculated as follows:

$$PCRES_r = \lambda_r^{res} \cdot \left[\alpha_r^{rese} \cdot \left(\frac{PCRES E_r}{\theta_r^{rese t}} \right)^{1 - \sigma_r^{res}} + (1 - \alpha_r^{rese}) \cdot \left(\frac{PC_{17,r}}{\theta_r^{res17 t}} \right)^{1 - \sigma_r^{res}} \right]^{\frac{1}{1 - \sigma_r^{res}}}, \quad (10)$$

$$PCRES E_r = \lambda_r^{rese} \cdot \left[\sum_{i=1, \dots, 5} \alpha_{i,r}^{rese} \cdot PC_{i,r}^{1 - \sigma_r^{rese}} \right]^{\frac{1}{1 - \sigma_r^{rese}}}. \quad (11)$$

C. Characteristics of the models

Table 5 presents the regional and sectoral dimensions of GEMINI-E3, as well as the sectoral aggregation used in this paper. Table 6 shows the useful demands in MARKAL-CHRES.

Table 6: MARKAL-CHRES Demand segments

RC1	Cooling
RCD	Clothes Drying
RCW	Clothes 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

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Table 5: Dimensions of the complete and aggregated GEMINI-E3 Model

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

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