Three Steps toward Modeling Swiss Post-2012 Climate Policies

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Abbreviations

BAU	Business As Usual
bbl	Barrel
bvkm/a	Billion Vehicle Kilometers per Year
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CHF	Swiss Franc
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent (calculated on the basis of global warming potential)
DWL	Deadweight Loss of Taxation
COP	Conference Of the Parties (UNFCCC)
ETS	Swiss Emission Trading Scheme
EU	European Union
EU ETS	European Emission Trading Scheme
EUA	European Union Allowances
FOEN	Federal Office for the Environment
G	Giga (10^9)
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GTT	Gains from Terms of Trade
HC	Households' consumption
IOT	Input-Output Table
IPCC	Intergovernmental Panel on Climate Change
J	Joule
JI	Joint Implementation
MCP	Mixed Complementary Problem
Mio. / M	Million / Mega (10^6)
NCCR	National Centre of Competence in Research
NOGA	Nomenclature Générale des Activités économiques
P	Peta (10^{15})
PSI	Paul Scherrer Institute
RES	Reference Energy System
SECO	Secretariat of Economic Affairs
SFOE	Swiss Federal Office of Energy
t	Ton
T	Tera (10^{12})
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar

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Abstract

This thesis presents three steps toward a more precise modeling of climate policies using hybrid models. Specific hybrid models have been devised and used to analyze different post-Kyoto Swiss climate policies.

Chapter 1 presents a rather simple hybrid model that allows to use a bottom-up model to obtain the fuel mix that would result from the application of economic instruments and technical regulations. The fuel mix is then dynamically used in a top-down model to asses the economic impacts of climate policies. The model is used in particular to assess the taxes that would be required if Switzerland would undertake GHG emissions abatement of 20% by 2020 and 50% by 2050.

Chapter 2 presents a more integrated hybrid model that also links residential investments and energy prices. It is used to assess the impacts of a number of ambitious climate policies in Switzerland, with a special focus on the dilemma between domestic GHG emissions abatement and the purchase of foreign emissions certificates.

Chapter 3 presents a more complex hybrid model that allows to take into account the various instruments and regulations for curbing the emissions in the industrial sector, the residential sector as well as the transport sector. Different from the first two chapters, where policy scenarios are rather simplified and consider mainly long term targets, the model is used to analyze the specific climate policies that were proposed as a result of the consultation procedure on the revision of the Swiss CO2 Law that took place before March 2009.

Keywords: Climate policy, Environmental taxation, Hybrid modeling, Transport, Residential, Welfare economics

Résumé

Cette thèse présente trois étapes visant une modélisation plus précise des politiques climatiques au moyen de modèles hybrides.

Le premier chapitre présente un modèle hybride relativement simple qui permet l'utilisation d'un modèle "bottom-up" pour calculer le mix énergétique dans le secteur résidentiel qui résulterait de l'implémentation d'instruments économiques et de règlementations techniques. Le mix énergétique est utilisé dynamiquement par un modèle "top-down" pour évaluer les impacts économiques des politiques climatiques. Le modèle est utilisé en particulier pour évaluer le niveau des taxes qui seraient nécessaires pour atteindre des objectifs de réduction des émissions de gaz à effet de serre de 20% d'ici à 2020 et de 50% d'ici à 2050.

Le second chapitre présente un modèle hybride plus intégré introduisant les investissements dans le secteur résidentiel et les prix des énergies comme variables de couplage. Il est utilisé pour évaluer des politiques climatiques ambitieuses pour la Suisse. L'accent est cette fois mis sur le dilemme entre les abattements domestiques et l'achat de certificats d'émissions.

Le troisième chapitre présente un modèle couplé plus complexe qui prend en compte différents instruments envisagés pour réduire les émissions dans le secteur industriel, le secteur résidentiel ainsi que dans le secteur des transports. En contraste avec les premiers chapitres dans lesquels les scénarios politiques sont relativement simplifiés, ce modèle permet l'analyse détaillée des politiques climatiques résultant de la procédure de consultation sur la révision de la Loi sur le CO_2 qui s'est terminée en mars 2009.

Mots-clés: Politique climatique, Taxes environnementales, Modélisation hybride, Transport, Résidentiel, Economie du bien-être

Foreword

This thesis is presented in the so-called "article" format. As a consequence, it contains a number of repetitions in the descriptions of the models and the references to literature dealing with hybrid modeling. This allows the reader to consider each chapter independently. In the annexes, cross-references have been made whenever possible.

The reader should also bear in mind that each chapter has been devised with a different hybrid model. Therefore, comparisons between the results of the various chapters should be undertaken with care.

Introduction

The United Nations' Secretary General, Mr. Ban Ki-moon, referred to climate change as "the greatest collective challenge we face as a human family". Indeed, not only a major change in the earth climate could have dramatic consequences on human societies and the environment but any attempt to mitigate the cause of human induced climate change have important consequences on our economies largely powered by fossil fuels. At the point where global international agreements need to be reached if we want to keep the hope of avoiding the major changes announced by climate scientists (see IPCC, 2007a), nations around the globe are evaluating the costs of mitigating greenhouse gas (GHG) emissions and designing efficient and acceptable climate policies.

Switzerland represents a small share of GHG emissions but is strongly engaged in meeting its abatement objectives and has proved to be at the forefront of international climate negotiations[1]. With 7.6 million inhabitants, GHG emissions amounted 51.3 million ton of CO_2 equivalent ($MtCO_2eq$) in 2007, slightly down from the 1990 level (52.7 $MtCO_2eq$). Since electricity is largely produced from hydro (56%) and nuclear (39%), transportation and housing are responsible for the major part of GHG emissions (see Figure 1).

Back in 1999, the Swiss Parliament adopted the Swiss CO_2 Law (Swiss Confederation, 1999), which entered into force on 1st May 2000, aiming at a 10 per cent reduction of CO_2 emissions below 1990 levels by 2010. Later, on 9 July 2003, Switzerland ratified the Kyoto Protocol to the UN Framework Convention on Climate Change with the objective to reduced all GHG emissions by 8 per cent below 1990 levels in the commitment period 2008-2012. The Law encompasses various

[1] e.g. the proposal of the Swiss ex-president M. Leuenberger to introduce a global carbon tax at the $12^{t}th$ Conference of the Parties or the proposal T. Kolly and O. Schwank at the 28th sessions of the Subsidiary Bodies of the UNFCCC to use the revenue of such a global carbon tax for solidarity in financing adaptation.

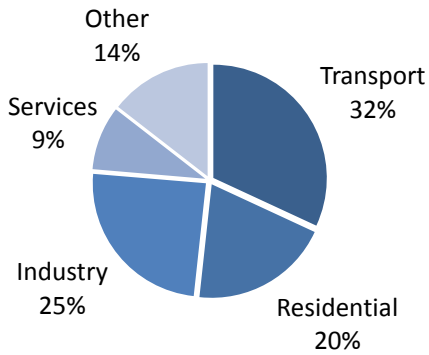

Figure 1: Sectoral contributions to Swiss GHG emissions (2007)

instruments to reach both of these objectives: (1) voluntary measures by the economy and individuals[2], (2) a CO_2 tax, if the voluntary measures are not effective enough, (3) measures taken in other policy areas and having a positive impact on climate and (4) the exchange of emission allowances and other flexibility mechanisms of the Kyoto Protocol. Special partial targets for combustible fuels (-15%) and transport fuels (-8%) have also been incorporated in the law. In 2007, the Federal Council has adopted an ordinance introducing an incremental CO_2 tax on combustible fuels (Swiss Confederation, 2007). As of 2010, level of this tax will be increased from 12 to 36 CHF. Furthermore, among the voluntary measures by the industry, the "Climate Cent" initiative is worth mentioning (Niederberger, 2005; Swiss Federal Office of Energy, 2006). Since October 2005, the Climate Cent Foundation is funded by a charge levied on all imports of petrol and diesel at a rate of 1.5 cent per liter. The Foundation invests into projects designed to reduce greenhouse gas emissions both in Switzerland and abroad — using the flexibility mechanisms of the Kyoto protocol: Clean Development Mechanism (CDM) and Joint Implementation (JI) — and is committed to reducing 12 $MtCO_2$, of which at least 2 $MtCO_2$ in Switzerland, over the period 2008-2012.

In the framework of the revision of the Swiss CO_2 Law for the post-2012 period and in view of the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change, the Federal Office for the Environment (FOEN) has proposed a set of instruments and two levels of abatement to define the Swiss climate policy for the post-2012 period. As it is the case in the European Union (European Commission, 2009a), a range of instruments are envisaged but a number of questions are still under discussion. This thesis sheds some light

[2]see Baranzini et al. (2004) for details about Swiss voluntary measures.

on some of them through the assessments of different aspects of Swiss climate policies using hybrid models.

Brief state of research

Policy makers rely on economists and their models to evaluate both the effects and the costs of implementing the economic instruments that are required to reduce GHG emissions. Two main families of models have been traditionally used for this purpose: top-down and bottom-up models. More precisely, computable general equilibrium (CGE) models and energy-systems models, such as MARKAL and TIMES, have proved particularly adapted to analyzing the long-term aspects related to climate change. Both model types have known advantages and drawbacks. CGE models are particularly adapted to represent the complex interactions in the economy whereas the MARKAL family of models allow for a precise description of technologies and respect the law of conservation of energy.

Combining the advantages of both model types is not a novel idea but only recently applied hybrid models are being developed and used for policy analysis purposes (Hourcade et al., 2006). Different coupling approaches have been used by various authors, but they can be grouped in two categories. In the first category (e.g. Drouet et al., 2005a; Schäfer and Jacoby, 2006), complete CGE and bottom-up models are kept separate and coupled to complement each other through the exchange of a number of variables or parameters. In the second category (e.g. Böhringer and Rutherford, 2006; Böhringer and Rutherford, 2008; Frei et al., 2003; Manne and Richels, 1992; Messner and Schrattenholzer, 2000), a reduced or partial form of one of the model types is incorporated into the other.

Though the underlying idea of the first category of models is not new — the first coupling of an econometric model of the US economy with an energy model was undertaken in Hoffman and Jorgenson (1977) — to date, the integration of large-scale complex top-down and bottom-up models remains unrealistic in terms of the computing power that would be required to solve them (see Bauer et al., 2008, for an example based on a macroeconomic growth model). Only very recent developments put forward in Böhringer and Rutherford (2009) let us envisage that the integration of a complete complex bottom-up model in a large CGE model could be possible through a single Mixed Complementary Problem (MCP) formulation, an approach used earlier but only with stylized or simplified

models (e.g. Böhringer and Rutherford, 2006; Frei et al., 2003). With that in mind, in the framework of an analysis of the policies envisaged in Switzerland for the post-Kyoto period, the so-called soft coupling approach was retained all along this research with the aim of devising and testing new methods allowing a better communication between top-down and bottom-up models.

Objectives

The objective of this research was to estimate the efficiency and the consequences of GHG mitigation policies for the post-2012 period, with a special focus on the transportation and housing sectors in Switzerland. Because existing top-down and bottom-up models alone do not allow for a precise analysis of the effects of climate policies in those sectors nor do they allow for analyzing specific sectoral policies, the development of new hybrid models was envisaged. The research was divided in three consecutive steps.

On the basis of the work undertaken in Drouet et al. (2005a) and other relevant scientific literature, the first step was to develop a simple hybrid model coupling GEMINI-E3 and a MARKAL model for the residential sector, while keeping both models relatively unchanged. Such a model was aimed at identifying the potential of the coupling procedure, while assessing stylized climate policies.

A second step was dedicated to the development of a second hybrid model, encompassing an international emissions certificates market and a precise accounting of investments and energy prices in the residential sector. This model was used to analyze ambitious climate policies, such as climate neutrality, and compare the welfare effects of domestic GHG emissions abatement and the purchase of emissions certificates.

A third step focused on a precise modeling of real world potentially "acceptable" Swiss climate policies, with a hybrid model encompassing both transport and residential bottom-up representations. The model was use to assess the welfare impact of the envisaged policies and, through a comparison with a uniform tax applied across the whole economy, evaluate the additional welfare cost of the compromises made in order to achieve acceptable policies.

Methodology

The principal building block of all hybrid models developed in this research is the GEMINI-E3 model (see Bernard and Vielle, 2008, for a detailed description). GEMINI-E3 is a global dynamic-recursive CGE model which is particularly well fitted to analyze problems linking energy, environment and economic issues. Indeed, through its representation of the economy in 18 sectors, among which five are energy sectors, its precise representations of indirect taxation and international trade and transport, it allows to asses the impacts of a great number of climate policies, both regional and international. It has been used, for example, 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). A version of GEMINI-E3 has also been developed with an extended representations of the electricity sector through the the integration of major electric generation technologies (Bernard and Vielle, 2009).

Like all CGE models, GEMINI-E3 nevertheless falls short when it comes to analyzing policies targeting sectors where numerous diverse technologies are at stake. The residential and the transportation sectors are perfect examples as they use a multitude of technologies, from different heating systems and electrical appliances to various types of private cars and trucks. In Switzerland, considering the low carbon intensity of the electricity production and the importance of the service sector in the economy, the major contributor to the nation's GHG emissions are precisely the residential and the transportation sectors. As a consequence, possibly even more than for other countries or regions, the use of hybrid models seems particularly required for modeling Swiss climate policies.

The residential and transportation sectors are described with great detail in the Reference Energy System (RES) of the Swiss MARKAL model taken over and further developed by Schulz (2007). Indeed, 173 technologies represent the various energy uses in Swiss homes and 184 technologies represent the vehicles that transport people and goods across Switzerland. Therefore, in collaboration with researchers at the Paul Scherrer Institute (PSI), we have extracted the two

sub-models from the complete Swiss MARKAL model, the so-called MARKAL-CHRES and MARKAL-CHTRA, and amended them so that they could exchange data with an iterative coupling module.

The coupling modules' functions and the number of coupling variables vary across the chapters of this thesis. Detailed descriptions of the three coupling methodologies are presented in sections 1.4, B.1 and 3.2.3.

In order to perform the coupling the GEMINI-E3 model original Stone-Geary utility have been turn into nested constant elasticity of substitution (CES) functions. Moreover, the nests in the CES functions which are linked to the MARKAL models, the elasticity parameters are set to 0, turning those nests to a Leontitef formulation. The use of the data coming from MARKAL in GEMINI-E3 is nevertheless slightly different in the three chapters. In the first chapter, the residential fuel mix is used to dynamically calibrate the shares parameter and the variation of the upper nest is fixed to the variation of total energy consumption observed in MARKAL. In the second and third papers, on top of calibrating the energy and investments shares, the variation of the total energy used in MARKAL is used to calibrate an efficiency parameter that not only allows for reflecting the variations in total energy use or investments but also influences the prices of energy and investments. This adequately reflects that investments in cleaner energies are more expensive than traditional ones. In the third chapter, the GEMINI-E3 model — thanks to an additional disaggregation of the transport sector — also allows for a modal switch and provides MARKAL-CHTRA with the variations of the transport demands.

Plan of the thesis

This thesis has been devised in the framework of the National Centre of Competence in Research (NCCR) Climate research program and under the auspices of the Research group on the Economics and Management of the Environment lead by Professor Philippe Thalmann. It is composed of three articles which have been submitted to international scientific journals and whose results have been used in reports to the Federal Office of the Environment (FOEN). Each paper is the result of collaboration with other universities, as promoted by the NCCR programs.

The preparation of the three articles has required some preliminary work, in particular the preparation of Swiss Input-Output tables (IOT) compatible with those of the GTAP database (Dimaranan, 2007). Indeed, the GTAP provides a IOT for Switzerland which is not comparable with the one developed in Nathani et al. (2006) and published by the Swiss Statistical Office. Therefore, in order to have comparable results with other studies about Switzerland, the vast majority of which use the IOT from the Swiss Statistical Office, it was a prerequisite to transform the Swiss IOT so that it meets the GTAP requirements, both in terms of structure and international trade flows. This transformation work is duly documented in two internal working papers (Sceia et al., 2007, 2009c). The first describes the transformation of the Swiss IOT into the 18 sectors used in the first two papers. The second presents the transformation of the IOT with disaggregated transport sectors presented in Infras (2006) into the 32 sectors used in the third paper.

The first paper is written together with Juan-Carlos Altamirano-Cabrera, Laurent Drouet, Thorsten F. Schulz and Marc Vielle. In this paper we couple the GEMINI-E3 model with a residential energy model to perform an integrated assessment of the global, national and sectoral impacts of different CO_2 mitigation policies. The paper presents the models, the coupling methodology and assesses various policies using the coupled models.

The coupling procedure we have implemented allows for estimating a CO_2 tax corresponding to a national CO_2 emissions target. Furthermore, it allows for modeling technical regulations aimed at increasing the energy efficiency of the technologies used in the residential sector. Finally, the coupled model allows an integrated analysis of the implication of the policies on the Swiss and the global economy as well as on the Swiss residential sector energy consumption.

In our coupling procedure, we use a version of GEMINI-E3 with six regions representing the world economy as well as a Swiss residential sector's energy model (MARKAL-CHRES). The coupling of the models is undertaken by a simple iterative procedure that seeks to reach the target emissions through the control of the value of the tax, while using the residential fuel mix of MARKAL-CHRES in GEMINI-E3.

When comparing the original GEMINI-E3 and the coupled model, it is in-

teresting to note that a pure CGE model like GEMINI-E3 allows for stronger abatement than the coupled model when it comes to relatively small taxes. Nevertheless, it is not able to model the substitution to future efficient but expensive technologies when taxes over 100 USD/tCO_2eq are introduced.

In the framework of the revision of the CO_2 Law for the post-2012 period, the Swiss federal council decided to follow similar targets as first announced by the European Commission, i.e. a 20% reduction of GHG by 2020 and a 50% reduction by 2050. In order to achieve those emission targets various options are envisaged. First, we implement emission taxes applied across the whole Swiss economy, influencing both the production sectors and the households by changes in relative prices. We analyze two types of taxes, first a tax that increases linearly up to the target year and, secondly, a constant tax, which has a fixed value from 2008 till 2050. We also compare CO_2 taxes with a tax covering all GHG. Secondly, we implement technical regulation in the residential sector with the aim of restricting investments to energy efficient technologies. We compare the energy efficiency of each technology with the average efficiency of all technologies allowing for satisfying the same final energy demand. Then, as of 2015, we restrict households' investments to those technologies having an energy efficiency superior or equal to the average. Finally, we combine both instruments.

We find that in Switzerland, without emissions trading mechanisms, the implementation of an increasing GHG tax reaching more than USD 200 per ton of CO_2 equivalent would be necessary in order to achieve a GHG abatement of 50% in 2050. With such levels of taxation, we also find that technical regulations do not bring additional incentives to abate emissions. We also present the consequences of the implementation of such taxes on the Swiss economy and on the residential sector in particular.

The second paper is written together with Juan-Carlos Altamirano-Cabrera, Thorsten F. Schulz and Marc Vielle. Apart from presenting further developments of the coupling procedure, it sheds some light on the dilemma between domestic abatement and the purchase of foreign emissions certificates.

The idea of Swiss neutrality with regard to greenhouse gas emissions is at the upfront of current policy discussions. With global prices of carbon at levels far from the Swiss marginal abatement costs, this neutrality would be mainly

achieved by means of large purchases of CO_2 certificates. This could jeopardize 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. However, 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, considering that they are producing an important share of high energy goods consumed in Switzerland. The share of embodied emissions, i.e. the net emissions resulting for the production of imported and exported goods, could account for up to 80% of the total domestic emissions (Jungbluth et al., 2007). Therefore, improving the energy efficiency abroad through certificates' purchases would somehow also reduce the impact of the Swiss consumption on the global climate. Accounting for embodied emission would change the approach to international climate negotiations and policies since so far the emissions relative to the production are counted in the producing countries and not in the consuming ones. Recent studies tend to show that embodied emissions might play a crucial role in future international negotiations, in particular in the case of China (e.g. Wang and Watson, 2008).

The climate problem of developed countries is two fold. On one side, they have to reduce their domestic emissions in order to meet stringent long term per capita targets and, on the other side, they should help developing countries to achieve sustainable development if they do not want to see their own efforts canceled. To achieve these objectives and to profit from the mechanisms implemented in the framework of the Kyoto protocol (e.g. CDM), developed countries could implement national taxes, targeting domestic abatement, whereas the revenue of those taxes could be used to purchase certificates and therefore contribute to sustainable development. Furthermore, the purchase of CDM credits could also be used to offset the emissions caused by the production of goods which are imported for consumption in developed countries.

The paper aims at quantifying and comparing the consequences of various ambitious objectives in Switzerland, such as neutrality or sustainability, with an emphasis on the welfare effects. We use a coupled top-down bottom-up model, which allows for a precise technological specification of the Swiss residential sector, as it encompasses a great potential for GHG emissions abatement, without losing the national and global economic picture.

In our coupling procedure, we use a six regions version of GEMINI-E3 representing the world economy, as well as a Swiss residential sector's energy model (MARKAL-CHRES). Compared to the first paper, the coupling procedure has been further improved to allow GEMINI-E3 to be calibrated not only to the fuel mixes of the MARKAL-CHRES but also to the variations in investments caused by the introduction of the tax.

In order to set a realistic framework for the simulations, we have defined three options for international policies ("low", "mid" and "high") based on various levels of commitment that could be agreed during the next round of international negotiations. All regions are allowed to trade emissions certificates among themselves.

In Switzerland, we consider a tax that would ensure that both domestic and total emission targets could be achieved; the total emissions target considers both the domestic abatement and the net trade of certificates. The tax would be set at a level such that its revenues are sufficient to purchase the emissions certificates required to offset the Swiss emissions up to the defined total emissions target and at least high enough to ensure the domestic emissions. In the second case the excess tax revenue would be redistributed as a lump-sum transfer. We define two variations of four major scenarios, one allowing an unlimited purchase of emissions certificates abroad and another imposing a minimum domestic abatement of 50% by 2050. In terms of total abatement targets by 2050 compared to 2001 levels, the four scenarios can be summarized as follow: (1) the "50%" scenario aims at achieving a 50% reduction; (2) the "sustainable" scenarios aims at a 75% reduction; (3) the "neutral" scenario, which follows the climate neutrality idea, aims at a 100% reduction and (4) the "zero footprint" scenario should reach -180% (including full compensation for emissions embodied in imports).

We find that 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 2tCO_2eq/cap while ensuring at least 50% domestic abatement through the implementation of a domestic progressive GHG tax reaching 144 USD_{2001}/tCO_2eq in 2050. In this paper we present detailed results for the various international scenarios, we describe the impacts of all scenarios on the Swiss economy as well as on welfare, including the terms of trade, and we analyze the contribution of the Swiss residential sector to the overall abatement effort under the various scenarios.

The third paper is written together with Juan-Carlos Altamirano-Cabrera, Marc Vielle and Nicolas Weidmann. It's main objective was to analyze the post-Kyoto climate policy proposals resulting from the consultation procedure on the revision of the Swiss CO2 Law that took place from December 2008 to March 2009. As expected, the proposals are far from the idea brought forward by the Swiss ex-president M. Leuenberger at the COP12, i.e. a global uniform carbon tax. Indeed, arguments relative to competitiveness and carbon leakage as well as the example of the neighboring European Union, pushed the FOEN to propose a complex combination of instruments with sector specific abatement targets.

There is no doubt that influential economic sectors, through their lobbying activities, can influence policy making. With regard to climate change, various studies have been undertaken on the acceptability of climate policies. Buchanan and Tullock (1975) show that that regulations tend to be more acceptable than taxes despite their lesser efficiency. Felder and Schleiniger (2002) consider how redistribution schemes can increase the acceptability of climate policies. Fredriksson (1997) shows that lobbying activities can negatively influence CO_2 abatement levels in case of abatement subsidies. Böhringer et al. (2009) analyze the allocations in the EU-ETS market and identify the excess burden induced by over-generous allocations to some important sectors. In this paper we are not interested in devising more acceptable policies or analyzing the lobbying activities that led to the actual proposals for the revisions of the Swiss CO_2 Law but rather in the effect on welfare of the resulting policies and the comparison with a uniform tax achieving the same targets.

We evaluate the two scenarios under consideration, a first one where international agreements would target a rather limited abatement, and a second one where stronger abatement would be agreed upon by all world nations. The two scenarios define specific targets for three parts of the economy: major energy intensive industries, the transport sectors and all other sectors using combustible fuels. In both scenarios various instruments are used to meet the targets: (1) a levy on transport fuels, (2) an emissions trading system (ETS) for energy intensive industries and (3) a CO_2 tax on combustible fuels. Furthermore, a building improvement program and technical regulations of passenger cars would also contribute to the abatement effort.

In order to model the two scenarios as well as their international framework,

we have developed a hybrid model suitable for integrating all the envisaged instruments and targets. Our hybrid model is composed of a six regions version of GEMINI-E3 complemented by MARKAL-CHRES and MARKAL-CHTRA, two energy models describing respectively the Swiss residential and transportation energy systems. The models are linked by the exchange of coupling variables and they run iteratively until a defined threshold on the variation of the taxes is reached.

Using our coupled models, we find that both scenarios do not have dramatic impacts on the Swiss economy and that (1) a few cents per liter of gasoline or diesel would be sufficient to offset the emissions in the transport sector; (2) depending on the chosen scenario, the price of Swiss ETS emission rights could vary between 8 and 30 USD_{2008}/tCO_2eq in 2030; but (3) the tax on heating fuels could reach 250 USD_{2008}/tCO_2eq to allow the 35% of abatement expected from combustible fuels by 2020. As a whole, the ETS and transport sectors would undertake more domestic abatement than the minimal share envisaged by the policies, leaving up to 3.5 $MtCO_2$ of "un-purchased" foreign certificates. Finally, we show that a uniform tax applied across the same sectors would be more efficient as it would trigger lesser welfare costs.

The following three chapters contain the papers summarized above. They are followed by a conclusion that highlights the major achievements and proposes ideas for further research.

Chapter 1

Integrated Assessment of Swiss GHG Mitigation Policies After 2012 — Focus on the Residential Sector

This chapter is a slightly amended version of the paper *"Integrated Assessment of Swiss GHG Mitigation Policies After 2012 — Focus on the Residential Sector"* written by André Sceia, Juan-Carlos Altamirano-Cabrera, Laurent Drouet, Thorsten F. Schulz and Marc Vielle (Sceia et al., 2008), a NCCR working paper also submitted to the peer-reviewed journal Environmental Modeling and Assessment.

Abstract

The residential sector presents a great potential for greenhouse gases (GHG) mitigation. We perform an integrated assessment of different mitigation policies for Switzerland focusing on the residential sector. We analyze the case of pure incentive taxes and technical regulations. For our analysis, we have coupled a general equilibrium model with a Swiss residential energy model. We find that an increasing GHG tax reaching more than 200 USD_{2000}/tCO_2eq is necessary to reach a target of 50% reduction of GHG emissions in 2050. Finally, we find that

technical regulations do not provide additional abatement incentives.

Keywords: Swiss residential sector, Climate policy, Top-down and bottom-up

1.1 Introduction

In many industrialized countries, the residential sector accounts for an important and increasing share of greenhouse gases (GHG) emissions. For instance, in 2005, the Swiss residential sector was responsible for 22.3% of total GHG emissions. These emissions are mainly due to the combustion of light fuel oil used for room and water heating. When we add the emissions from transport to those of the residential sector, they represent more than half of the total GHG emissions, a huge proportion when we consider that industry was only responsible for 21.6%. This Swiss specificity is mainly due to two factors. First, the major part of high energy goods are imported into Switzerland; indeed, the Swiss economy is more based on services than on heavy industry. Secondly, electricity is produced at almost 95% with hydro- and nuclear power plants. As a result, the residential sector presents some of the more interesting low hanging fruits with regard to GHG abatement. Energy saving investments like insulation will become increasingly profitable if energy prices keep on rising. Moreover, efficient technologies for space and water heating, e.g. heat pumps and solar, are available today for both houses and apartment buildings. With that in mind, it makes perfect sense for Swiss policy makers to pay a special attention to the residential sectors when devising climate policies.

The current Swiss climate policy will comply with the objectives fixed in the Kyoto Protocol, though they are not sufficient to meet the objectives of the current CO_2 Law that prescribes a further emissions reduction. The Law provides for a reduction of 2.9 million tons of CO_2. According to current estimates, there will be excess emissions of 0.5 million tons of CO_2 with respect to the objective fixed by the Law. Considering the post 2012 climate policy, in February 2008, the Swiss Federal Council decided to launch a revision of the CO_2 Law. It decided to follow similar targets as the European Union, i.e. at least 20% reduction of GHG by 2020 and 50% by 2050. A consultation procedure on this revision was launched in December 2008 in order to compare various envisaged instruments: a pure incentive tax (the revenue of which would be redistributed to households), a

tax financing national or international abatement or adaptation measures as well as technical regulations.

The objective of this paper is to assess some of the instruments envisaged for the revision of the Swiss CO_2 Law. We focus on the residential sector given its potential when it comes to GHG abatement. To attain our objective we devise a coupled model, combining a global economic model (GEMINI-E3) with a Swiss residential energy use model (MARKAL-CHRES). The benefit of coupling a top-down Computable General Equilibrium (CGE) with a bottom-up energy use models is twofold. On the one hand, it allows estimating the consequences of national policies on the Swiss economy and more specifically on the Swiss residential sector. On the other hand, the coupled model allows testing policies targeting energy use in the Swiss residential sector with a very detailed representation of the energy technologies both used and available in that sector, and to asses the impact of those policies on the overall economy.

The coupling between top-down and bottom-up models has already been explored in the literature (see, among other, Böhringer, 1998; Drouet et al., 2005b; Löschel and Soria, 2007; Manne and Richels, 1992; Pizer et al., 2003; 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 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 from their original formulation. Therefore, both models have been kept separate, while linking them with a coupling module. In Manne and Richels (1992), a reduced CGE model is incorporated in a bottom-up model. In contrast, we tried to keep our CGE as complete as possible, allowing a more complete and realistic interpretation of the results for the current consultation procedure on the future of the Swiss CO_2 law. Finally, until now, the only coupling paper specifically targeted to the Swiss residential sector is Drouet et al. (2005b). They have devised an hybrid model where the residential sector energy consumption is removed from the top-down model and replaced by an exogenous and separate bottom-up model.

This paper aims at further developing the coupling methodology, dynamically integrating the results from the bottom-up model into the top-down model without touching the interactions between the residential sector and the rest of the economy. The coupling procedure we have implemented allows estimating CO_2 or GHG taxes in response to national emission targets. Furthermore, it allows simulating technical regulations in the residential sector. Finally, the coupled model allows an integrated analysis of the implications of the policies on the Swiss and the global economy as well as on the Swiss residential sector. From our analysis, we find that in Switzerland, without emissions trading mechanisms, the rapid implementation of an increasing GHG tax reaching more than 200 USD per ton of CO_2 equivalent (USD/tCO_2eq) would be necessary in order to achieve a GHG abatement of 50% in 2050. With such levels of taxation, we also find that technical regulations do not bring additional incentives to abate emissions.

The paper is organized as follows: section 1.2 presents both the GEMINI-E3 and MARKAL-CHRES models, section 1.3 explains how the baseline scenario of the models has been calibrated, section 1.4 presents the coupling procedure and a sensitivity analysis of the coupled model, section 1.5 presents the policy scenarios, section 6 the numerical results and section 1.7 concludes.

1.2 Models

1.2.1 GEMINI-E3

The complete GEMINI-E3 is a dynamic-recursive CGE model that represents the world economy in 28 regions (including Switzerland) and 18 sectors. It incorporates a highly detailed representation of indirect taxation (Bernard and Vielle, 1998). For this study, we use an aggregated version of the model in 6 regions, i.e. Switzerland (CHE), European Union (EUR), other European and Euro-asian countries (OEU), 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 and government expenditures from the International Energy Agency (2002a,b, 2005), the OECD (2005, 2003) and the IMF (2004). For Switzerland, we used data from the 2001 input-output table devised at the Swiss Federal Institute of Technology (ETH) Zürich (Nathani et al., 2006), which we transformed into the GEMINI-E3 format (Sceia et al., 2007). All the data on emissions and abatement costs for non CO_2 GHG come from the (United States Environmental Protection Agency, 2006). For a complete description of GEMINI-E3 see Bernard and Vielle (2008). Various versions of the model have been used to analyze the implementation of economic instruments allowing for GHG emissions reductions in a second-best setting (Bernard and Vielle, 2000).

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.

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 1.1. The σ^x refer to the elasticity parameter of each node. Plain numbers in the figure refer to economic sectors, 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. Details about the equations used the residential nest of the CES function are presented in annex A.1. It is important to note that "other" inputs in the residential nest encompass construction costs related to the installation of energy related technologies (e.g. insulation and heat pumps) as well as the purchase of energy related equipments such as furnaces. Nevertheless,

it does not contain the construction of the buildings themselves. Furthermore, for Switzerland, only petroleum products are used as input in the transportation energy nest.

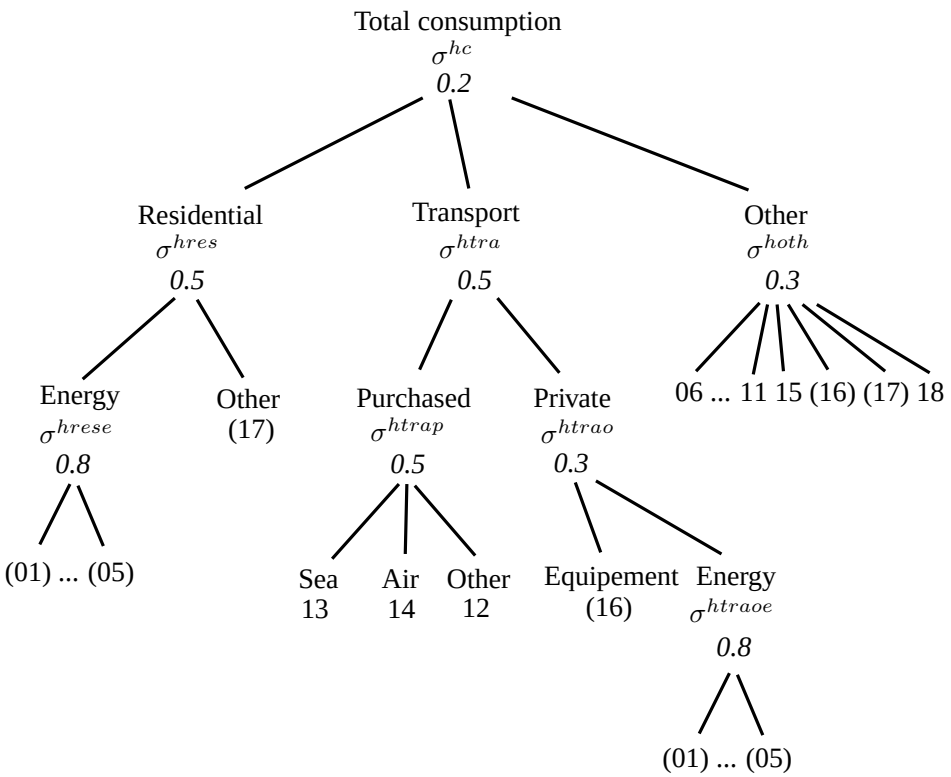

Figure 1.1: Structure of the households' nested CES utility function (σ^x : elasticity)

Finally, in order to better match the actual Swiss taxation scheme, we have differentiated excise taxes for heating oil from those of petroleum products used as transportation fuels. In order to do so, we introduced a basic excise tax ($ExTax_{base}$), fixed at the level of the 2001 residential excise tax, and a supplementary excise tax ($ExTax_{sup}$) applied only in the transportation sector. Therefore, in the residential sector, we use a final consumption price equal to $PC = (PB + ExTax_{base}) \times (1 + vat)$, where PB is the production price and vat the rate of value added tax. In the transportation sector, we add the supplementary excise and therefore $PC_{trans} = PC + ExTax_{sup}(1 + vat)$. This is equivalent to $PC_{trans} = (PB + ExTax_{base} + ExTax_{sup}) \times (1 + vat)$.

1.2.2 MARKAL-CHRES

The MARKAL-CHRES is an energy model describing the Swiss residential energy system. It models the private household establishments's energy consumption and related technical investments. It is based on the Swiss MARKAL model witch was recently taken over and further developed by researchers at the Paul Scherrer Institute (PSI) where it has been used, among other, to analyze the Swiss 2000W society initiative (Schulz et al., 2008). The MARKAL-CHRES is a subset of the complete Swiss model. It is restricted to technologies related to the residential sector and considers final energies as being imported with exogenous prices. The model contains 173 technologies using different energies sources, i.e. coal, oil, gas, electricity, wood, pellets and district heat.

The model base year (2000) is calibrated to the International Energy Agency (IEA) and Swiss General Energy statistics of the year 2000. The model has a time horizon of 50 years and is divided into eleven time periods each with a duration of five years except the base year (2000, 2001–2005, 2006–2010, . . . , 2046–2050). The residential energy sector of the model includes 13 energy demand segments (see Table 1.1). 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 USD_{2000} as currency, therefore all monetary value are discounted to year 2000 values using a 5% discount rate.

One of the particularities of the MARKAL-CHRES model is to describe precisely a set of technologies which allow energy savings in various processes. 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 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).

Table 1.1: 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

1.3 Baseline

We have taken into account the differences between the models to calibrate the baseline. First, whereas GEMINI-E3 annually simulates economic equilibrium from 2001 to 2050, MARKAL-CHRES minimizes the total discounted costs of 11 time periods between 2000 and 2050. Therefore, the MARKAL-CHRES data regarding the year 2000 have not been used for the coupling since GEMINI-E3 base year is 2001. Moreover, in order to obtain annual data from MARKAL-CHRES, we have used a linear interpolation. Secondly, we have made some assumptions and aligned the emissions between both models as explained below.

1.3.1 Assumptions

In order to perform a first coupling attempt we have assumed that world energy prices are only slightly affected by changes in the energy use in Switzerland and are therefore kept fixed at the baseline levels in the MARKAL-CHRES. Moreover, the total households' consumption (energy and non energy), which could be used as a proxy for the useful energy demands in the the residential sector, does not greatly vary from the baseline to the counterfactual. Therefore, the useful energy demands in MARKAL-CHRES are kept constant.

Furthermore, in the MARKAL-CHRES model, 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^{2}year) multiplied by REA (Mio m^2). The Swiss Federal Office of Energy provides estimates of the REA until 2035. Values until 2050 are extrapolated.

In GEMINI-E3 population assumptions are based on the United Nations' medium scenario. 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 also use the projections from DOE (2006) for oil, gas and coal prices.

1.3.2 Emissions

We import the fuel mix from MARKAL-CHRES into GEMINI-E3 in order to align the emissions in the residential sector between the two models. The annual variation of the total energy consumption in GEMINI-E3 Swiss residential sector is aligned to the variation of the total use of energy in MARKAL-CHRES. Moreover, the shares between the different energies are defined using the fuel mix (see Chapter 1.4 for details). Furthermore, we set the growth of technical progress in the private transport energy nest and of general technical progress in 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). Figure 1.2 shows the baseline CO_2 and other GHG emissions calculated by GEMINI-E3 using the fuel mix from MARKAL-CHRES. Emissions of other GHG are transformed into CO_2 equivalent (CO_2eq) for comparison and summing requirements. They represent the amount of CO_2 that would have the same global warming potential, when measured over a specified timescale. The natural decline of emissions is partly due to the availability of costless abatement measures, but also to the existing energy and climate policy instruments (e.g. R&D, fuel taxes, regulations).

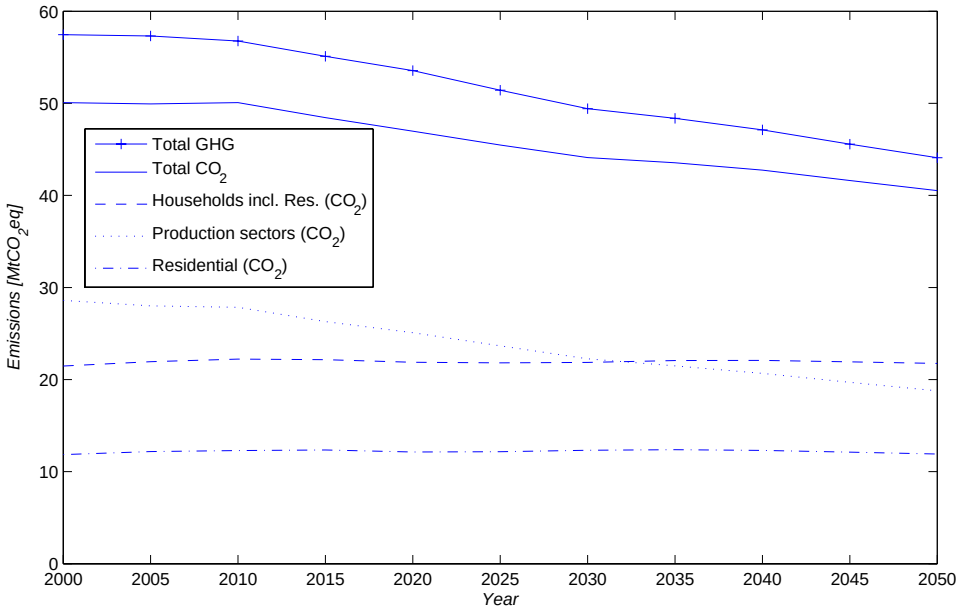

Figure 1.2: Baseline CO_2 and GHG emissions

1.4 Coupling

GEMINI-E3 and MARKAL models are complementary for two reasons. First, CGE models provide an explicit representation of the economy and are based on sound micro-economic foundations. Nevertheless, even with a rich disaggregate formulation they generally fail to depict precisely the evolution of substitution among technologies as well as the energy use and do not respect the physical energy conservation principles. In that respect, bottom-up models perform much better. In contrast, because they focus mainly on rich technology representation and cost minimization objectives, thus they fail to represent the complex market interactions which are dealt with by CGE models. Secondly, recursive dynamic CGE models, such as GEMINI-E3, have a myopic behavior, i.e. simulating one period at the time. Conversely, bottom-up models of the MARKAL family are perfect information perfect foresight model and minimize the costs of the system across the whole time frame. Hence, using MARKAL-CHRES to asses the evolution of the energy use in the residential sector of GEMINI-E3 allows introducing long term anticipations into GEMINI-E3. This is particularly useful when considering taxes which value is known to increase progressively over time.

Different from Drouet et al. (2005b), where the residential energy consumption

is subtracted from total consumption in order to calculate CO_2 emissions from the rest of the economy, we have used the MARKAL-CHRES fuel mixes in GEMINI-E3 residential nest to calculate CO_2 and other GHG emissions together with all other macroeconomic variables. In order to do so, the share parameters in the residential energy nest (α_{iCHE}^{resee}) (see equation A.4 in Appendix 1.4) are defined using the values calculated by the MARKAL-CHRES and the elasticity σ_{CHE}^{hrese} is set to 0. In other words, we use a Leontief formulation in the residential energy nest. When relative fuel prices change, following the introduction of a tax, the substitutions between the various energies in the residential sector is therefore computed by MARKAL-CHRES. Furthermore, the variation of total residential energy ($HCRESE$) between the baseline and the counterfactual is fixed, imposing the same variation as the one of the sum of the fuel mixes. This new approach is made possible by the introduction of a CES utility function that replaces the Stone-Geary function used in previous versions of GEMINI-E3. In this first coupling attempt using a CES utility function and similarly to what has be done in Drouet et al. (2005b), we do not link the capital investments simulated in MARKAL-CHRES and the equivalent consumption (residential - other) in GEMINI-E3.

1.4.1 Coupling method

In this paper we use a simple dichotomic procedure, which is sufficient in the case of a single control variable, in our case the CO_2 or GHG taxes. Indeed, in our coupled model, emissions in the target year are monotonic decreasing with respect to the tax. This ensures that our simple coupling module finds the unique optimal tax for each abatement target.

The coupling module functions as follows: we first initialize the minimum and maximum bounds for the tax (t_{min} and t_{max}), the tax level (tax), the emission target ($\bar{e}$) and the initial emissions calculated by GEMINI-E3 ($e = G(tax, fm)$). We run MARKAL-CHRES to calculate the fuel mix ($fm = M(tax)$) and then GEMINI-E3 to calculate the total emissions in the target year ($e = G(tax, fm)$) as long as the difference between emissions in the target year and the emission target is greater than a defined threshold ($|e - \bar{e}| > 0.01$) and the tax variation between two runs is greater than another threshold ($|tax_{-1} - tax| > 0.01$). If the total emissions are lower than the target we redefine the upper bound of

the tax ($t_{max} = tax$); otherwise we redefine the lower bound ($t_{min} = tax$). We store the tax level for future comparisons ($tax_{-1} = tax$) and define the new tax ($tax = t_{min} + (t_{max} - t_{min})/2$).

The variable fm is the fuel mix matrix in the residential sector calculated by MARKAL-CHRES and is defined as follows:

$$fm = \begin{pmatrix} fm_{coal,2000} & fm_{coal,2005} & \cdots & fm_{coal,2050} \\ fm_{gas,2000} & fm_{gas,2005} & \cdots & fm_{gas,2050} \\ fm_{petr,2000} & fm_{petr,2005} & \cdots & fm_{petr,2050} \\ fm_{elec,2000} & fm_{elec,2005} & \cdots & fm_{elec,2050} \end{pmatrix},$$

where $fm_{coal,t}$, $fm_{gas,t}$, $fm_{petr,t}$ and $fm_{elec,t}$ are respectively the energy consumptions of coal, gas, petroleum products and electricity in the year t.

Figure 1.3 presents this coupling schema. The tax is the variable that allows controling both models, the residential fuel mix is the coupling variable ensuring that GEMINI-E3 calculates emissions on the basis of the MARKAL-CHRES simulations and the total emissions in the target year are the optimization variable ensuring that the coupled models converge to the target defined by policymakers.

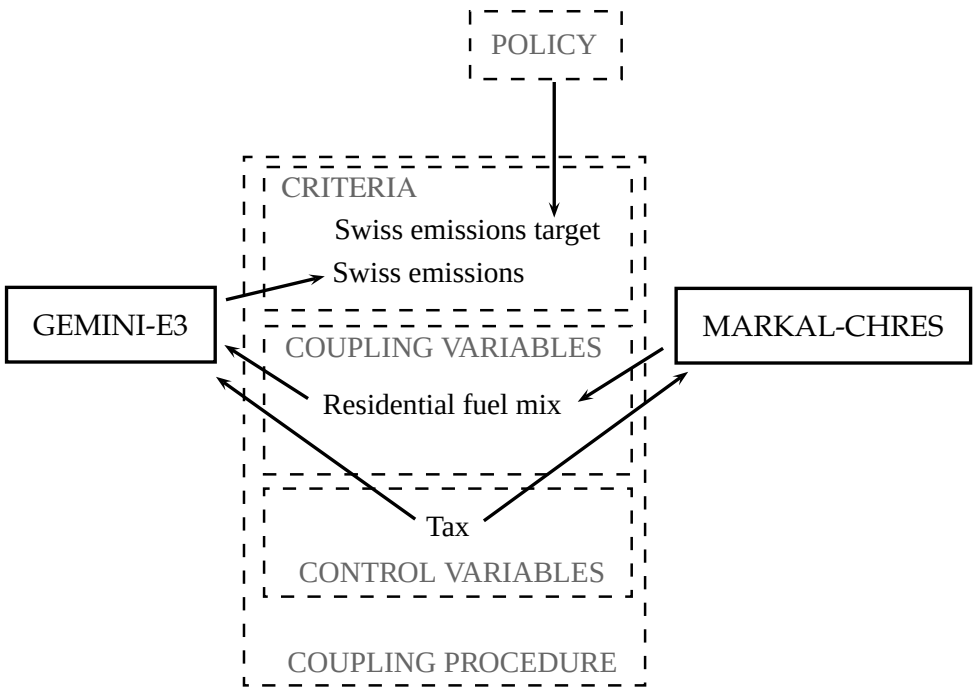

Figure 1.3: Coupling structure

1.4.2 Sensitivity analysis of the coupled model

Figure 1.4 shows the sensitivity of the model to various levels of taxation. The lines represent taxes of 0 (plain), 50 (dash-dot), 100 (cross), 150 (star) and 200 USD/tCO_2eq (circles); colors are used to differentiate between the various types of emissions (see legend). The figure shows that both the total CO_2 and total GHG emission decline strongly when the increasing tax is set up to reach 150 USD/tCO_2eq by 2050. With such taxation levels, the residential sector, which presents high substitution potentials in this coupled framework, exhausts all its abatement potential as early as 2035. The figure also demonstrates that private transportation, the other part of households' emission, is quite inelastic. This is a consequence of having only petroleum products as source of energy for households private transportation as well as having incorporated the existing differentiation in the taxation of petroleum products according to their use. The CO_2 tax affects more the relative prices of heating oil than those of gasoline or diesel.

Figure 1.5 shows the additional abatement in 2020 and 2050 at various levels of tax for both the original GEMINI-E3 and the coupled model. It is interesting to notice that a pure CGE model like GEMINI-E3 allows stronger abatement than the coupled model when it comes to relatively small taxes. Nevertheless, it is not able to model the substitution to future efficient but expensive technologies when taxes are over 100 USD/tCO_2eq. Therefore, only the coupled model enables us to reach the high levels of abatement we are expecting in 2050 with realistic taxation levels. We observe in Figure 1.4 that the abatement possibilities in the residential sector tend to be exhausted quickly when the tax level reaches 150 USD/tCO_2eq. As a consequence, in 2050, the total additional abatement tends to stabilize after having reached 16 MtCO_2eq.

1.5 Policy scenarios

In 2007, the Swiss Federal Council had decided that Swiss energy policy would be based on four pillars: the increase of energy efficiency, the promotion of renewable energy, the replacement and construction of electric power plants and international energy policy. These four pillars will support the climate policy targets and they should also support action plans aiming at a reduction of the use of fossil fuels by 20% by 2020, an increase of 50% in the use of renewable energy by

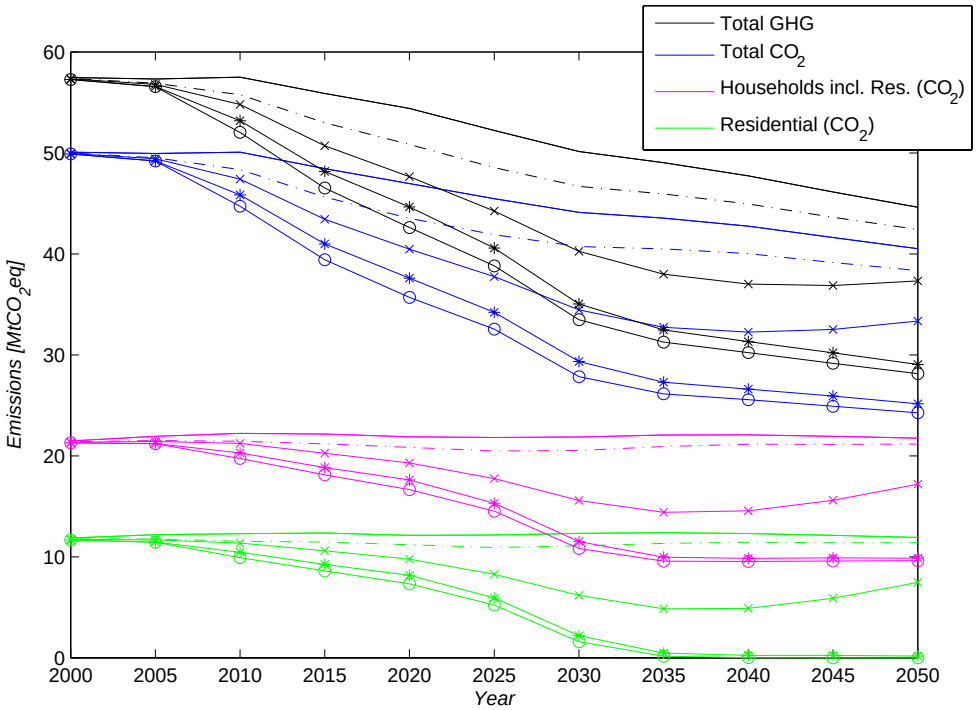

Figure 1.4: Impact on CO_2 and GHG emissions of various levels of increasing taxes – 0 (−), 50 (·−), 100 (×), 150 (∗) and 200 (∘) USD/tCO_2eq

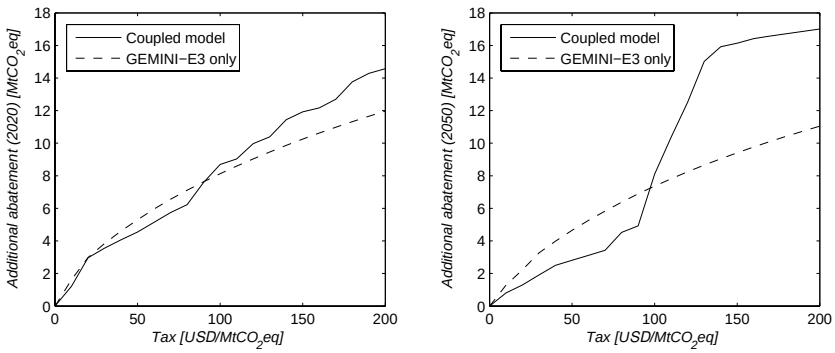

Figure 1.5: Comparison of GEMINI-E3 with the coupled model - Additional total abatement in 2020 (left) and 2050(right)

the same year and a limit of 5% on the growth of electricity consumption between 2010 and 2020.

In December 2008, the Swiss Federal Council launched a three-month consultation on two variants for revising the existing CO_2 law after it expires in 2012:

1. the same reduction targets as the European Union, i.e. 20% reductions of

GHG emissions relative to 1990 by 2020 and 50% by 2050; a pure incentive tax on all fossil fuels would be set to meet those targets, i.e. it would be responsive to economic growth, fossil fuel prices and the effects of other energy conservation and substitution measures; the revenues of the tax could be redistributed to households and firms or used to subsidize energy conservation measures; firms that reduce their emissions by as much as under the tax would get it refunded; they may purchase compensation abroad so long at it does not exceed one fourth of total reductions

2. a 50% reduction target for 2020 and full climate neutrality after 2030, provided the international community agrees on an ambitious climate regime; 17.8% of the reduction would be obtained by energy conservation and substitution measures, without specific tax; 32.2% would be obtained through the purchase of emissions certificates on world markets by the importers of fossil fuels; in order to make sure that they purchase the certificates, they would have to pay into a guarantee fund 36 CHF/tCO_2 (21 USD_{2000}), which they would recover when they prove the compensation of 50% of the imported CO_2; this puts a ceiling of 42 USD_{2000} on the price fossil fuel importers would pay for emissions certificates; if world prices exceed that ceiling, there would be no compensation and the target would be missed.

In this paper, we do not simulate exactly these policies but rather more stylized scenarios and focus on variant 1. In order to facilitate the transition between the current CO_2 Law, which targets only CO_2 emissions, and the future policies which encompass all GHGs, we have decided to consider objectives for both CO_2 and all GHG emissions. Among the policy instrument and measures under consideration, we have selected those which either focus on the residential sector or have a wide impact on the economy. As a consequence, we have decided to analyze pure incentive GHG and CO_2 taxes as well as technical regulations enforced in the residential sector. We study the potential abatement and the consequences following the implementation of both instruments separately as well as jointly. In this study, the tax revenues of the so-called pure incentive taxes are redistributed to households through lump sum transfers. Further studies could analyze the influence of various redistribution schemas or specific uses of the tax revenue.

We test three different scenarios. In the first scenario, we implement emission taxes applied across the whole Swiss economy, influencing both the production

sectors and the households by changes in relative prices. We analyze two type of taxes, first a tax that increases linearly up to the target year and, secondly, a constant tax, which has a fixed value from 2008 till 2050. We also compare CO_2 taxes with taxes covering all GHG.

The second scenario focuses on measures restricted to the residential sector and is not designed to achieve a specific abatement, therefore, it cannot be compared to the first scenario. In the second scenario, we consider the implementation of technical regulations which aims at restricting the residential investments in technologies considered inefficient as of 2015. In order to define the inefficient technologies, we compare the energy efficiency of each technology with the average efficiency of technologies satisfying the same final energy demand (see Table 1.1). The technologies having an energy efficiency below the average are considered inefficient. Then, as of 2015, we exclude households' investments in inefficient technologies. Technologies not using fossil fuels or electricity are not restricted, and in the case of residential heating, we do not consider heat pumps, neither in the calculation of the average efficiency nor in the list of restricted technologies given their high energy efficiency. Examples of inefficient technologies falling in the restricted list are incandescent and halogen lamps.

Finally, the third scenario considers the joint use of both instruments, trying to mimic the potential implementation of a *portfolio of measures* that have different fields of application. The next section presents the integrated assessment of our scenarios.

1.6 Results

In this section, we present the results of the scenarios described above from the perspective of their environmental effectiveness (i.e. emissions reduction) as well as their consequences on the Swiss economy and on the residential sector in particular.

1.6.1 Pure incentive tax

The results in Table 1.2 show that a 20% reduction of GHG emissions by 2020 requires a tax increasing to 97.9 USD/tCO_2eq on all GHG and the tax should

reach 201.6 USD/tCO_2eq to ensure a 50% abatement by 2050. The level of those taxes could obviously be reduced if the taxes were set uniformly across periods. Furthermore, when only CO_2 emissions are taxed, similar abatement levels require higher taxation levels, which could go up to almost 220 USD/tCO_2eq to abate GHG emissions by 50% in 2050. These results confirm that *without emissions trading*, achieving substantial abatement levels in Switzerland requires a significant level of taxation. In comparison, these levels of taxation are much higher than the CO_2 tax introduced in 2008 on heating and process fuels, which amounts to 12 CHF/tCO_2 and should grow to 36 CHF/tCO_2 in 2010.

In the case of a 50% abatement target, the model faces rigidities in private transportation where little substitution is possible even with distant horizons such as 2050. Modeling the transportation sector using an energy use model should better represent the substitution possibilities and therefore reaching similar targets with lower taxes (see chapter 3). The figures in italic, the intermediate (2020) or final (2050) abatement levels associated with the taxes, show that the taxation levels set out to reach the 2020 target would not allow reaching the 2050 objectives. Similarly, taxes allowing the model to reach the 2050 targets are either insufficient, if implemented in a progressive way, or too restrictive, when implemented uniformly across the whole period. If both the 2020 and 2050 objectives need to be met, the tax could be implemented progressively but not linearly. In that case, the annual increase in the first phase (before 2020) should be stronger than in the second phase.

Table 1.2: Abatement and pure incentive taxes in USD/tCO_2eq

	CO_2 tax		GHG tax	
Target	Increasing	Constant	Increasing	Constant
20% by 2020	105	93	98	89
% in 2050	*37*	*29*	*35*	*32*
50% by 2050	220	157	202	134
% in 2020	*18*	*27*	*17*	*25*

1.6.2 Technical regulations

We find that the use of technical regulations, as we have define them, has a limited impact on Swiss CO_2 and GHG emission. Figure 1.6 compares the baseline emissions with (lower line) and without (upper line) technical regulations in the residential sector. The impact of the technical regulations is slightly more important on CO_2 emissions than on total GHG emissions due to the targeting of the regulations on CO_2 intensive technologies. The maximum impact of the regulation is of about 2% around 2020.

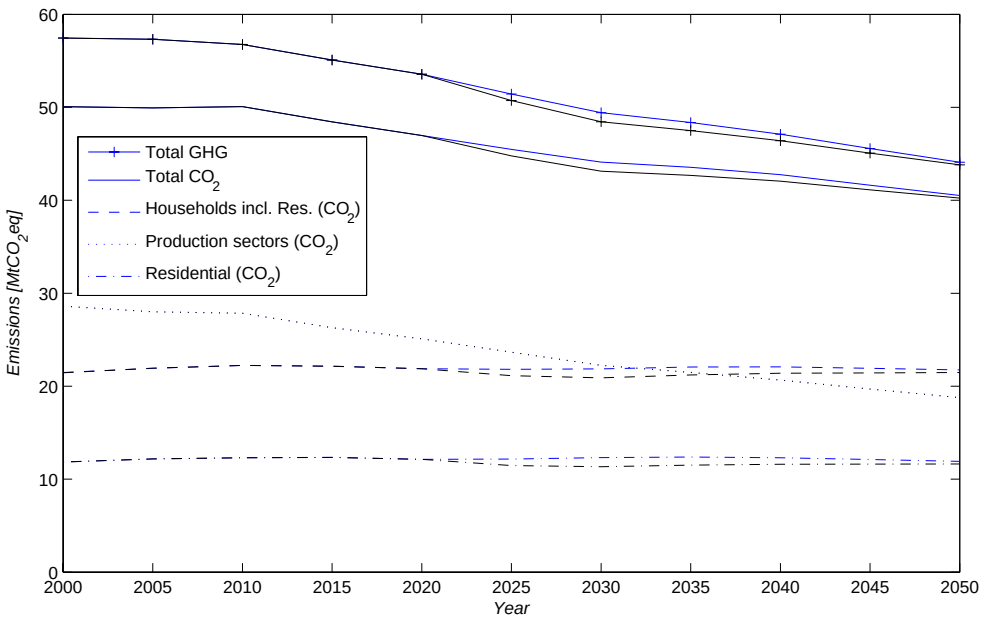

Figure 1.6: Impact of the technical regulations on the baseline CO_2 and GHG emissions

The reason for this limited effect on GHG emissions of the technical regulations as we have defined them partly lies in the definition itself. Indeed, the regulation does not take into account the energy efficiency of heat pumps when calculating the average energy efficiency of the technologies providing for room heating. Therefore, and in view of high investment costs required for technologies providing alternatives to oil burners, room heating remains a major consumer of light fuel oil despite the technical regulations. Including heat-pumps into the calculation of the average efficiency for room heating would further trigger a switch towards CO_2 free technologies.

Other measures than those we have modeled could have a greater impact

on emissions and would deserve further consideration. Among those, we can mention: financing a program promoting the energetic renovation of buildings, implementing technical regulations on vehicles, strengthening research on energy efficiency or accelerating technological transfer.

1.6.3 Joint use of technical regulations and taxes

When the coupled model takes into account the implementation of the technical regulations, the CO_2 and GHG taxes ensuring the abatement targets are not significantly different from those calculated without technical regulations. This is mainly due to the fact that the less efficient technologies are naturally abandoned by households since CO_2 or GHG taxes further reduce their competitiveness. Nevertheless, despite their little effect on CO_2 emissions abatement, technical regulations are worth to be considered. Our results show that, when combined with taxes, they provide a way to limit the increase of electricity consumption which is also on of the target of the future revision of the Swiss CO_2 law.

In view of the limited abatement obtained by the implementation of technical regulations, we concentrate the rest of the analysis on the first scenario.

1.6.4 Impacts on the Swiss economy

Table 1.3 shows the variations of GDP due to the pure incentive taxes defined in Table 1.2 for the years 2020 and 2050. The figures show that the impact of emission taxes on the Swiss economy is limited and, in all cases, would reduce GDP by less than half a percent compared to the baseline, even with taxes as high as 200 USD/tCO_2eq. Moreover, GHG taxes have a smaller impact on GDP than CO_2 taxes. The effects on GDP might be a little stronger if we forced the CGE part of the model to mimic the increased spending on equipment suggested by the MARKAL-CHRES. Indeed, the tax has an incidence on consumers' investment strategies, i.e. they invest in less polluting but more expensive technologies. When technical regulations are combined with taxes, we observe the same impacts on GDP.

In our assessment, only constant taxes set to meet the 2050 targets allow meeting both 2020 and 2050 targets. Nevertheless, increasing taxes have a higher

Table 1.3: GDP variations without technical regulations (in %)

Gas	Target	Tax	2020	2050
GHG	20% by 2020	Increasing	-0.17	-0.21
		Constant	-0.16	-0.17
	50% by 2050	Increasing	-0.11	-0.41
		Constant	-0.24	-0.36
CO_2	20% by 2020	Increasing	-0.19	-0.26
		Constant	-0.17	-0.18
	50% by 2050	Increasing	-0.12	-0.44
		Constant	-0.28	-0.39

chance to be accepted since their total cumulated impact on GDP from 2008 to 2050 is smaller. Figure 1.7 shows the impacts on the production sectors of a 219.7 USD/tCO_2 tax on CO_2 and a 201.6 USD/tCO_2eq tax on all GHGs. The only sector that strongly benefits from the introduction of the taxes is the electricity sector, due to the increased demand for electricity which is produced mainly CO_2 free in Switzerland. In the case that current nuclear power plants were replaced by combined cycle gas turbines, emission taxes would have to be higher and the electricity sector would not benefit as much from the introduction of the tax. The petroleum products sector is the most affected by the introduction of the taxes, together with other energy intensive sectors such as mineral products, agriculture and air transport. Not surprisingly, in our modeling framework, other transport (transport nec), which includes commercial road transport and rail, is not that much affected by the tax in view of the substitution between private and purchased transport.

Table 1.4 presents the contributions of households and economic sectors to CO_2 abatement as well as the contributions of the different greenhouse gases to total abatement. The major contribution to the CO_2 abatement effort is attributed to households with a share of 35%, followed by road and rail transport which accounts for 16.5% of the emissions reductions between 2001 and 2050. If we consider that in the baseline scenario a certain level of abatement is already achieved as a consequence of currently adopted policies, the share of households in the additional abatement is as high as 74%. All GHG contribute substantially to the overall abatement, in particular in the case of GHG taxation, with exception of fluorinated gases, which still increase despite the high levels of taxation. This

Table 1.4: Contributions (in %) to the emissions abatement between 2000 and 2050 (increasing taxes)

Sectors / Gases	GHG tax	CO_2 tax
Households	35.11	37.78
Transport nec	16.55	16.86
Services	8.64	8.92
Air Transport	4.90	5.06
Mineral Products	4.25	4.29
Consuming goods	3.25	3.29
Equipment goods	2.13	2.16
Petroleum Products	2.09	2.13
Paper products publishing	1.91	1.93
Metal and Metal products	1.86	1.87
Agriculture	1.09	1.10
Chemical, rubber, Plastic	0.99	1.01
Electricity	0.92	0.93
Forestry	0.34	0.34
Sea Transport	-0.04	-0.02
CO_2	83.97	87.66
CH_4	9.33	7.88
N_2O	7.25	6.62
Fluorinated gases	-0.55	-2.16

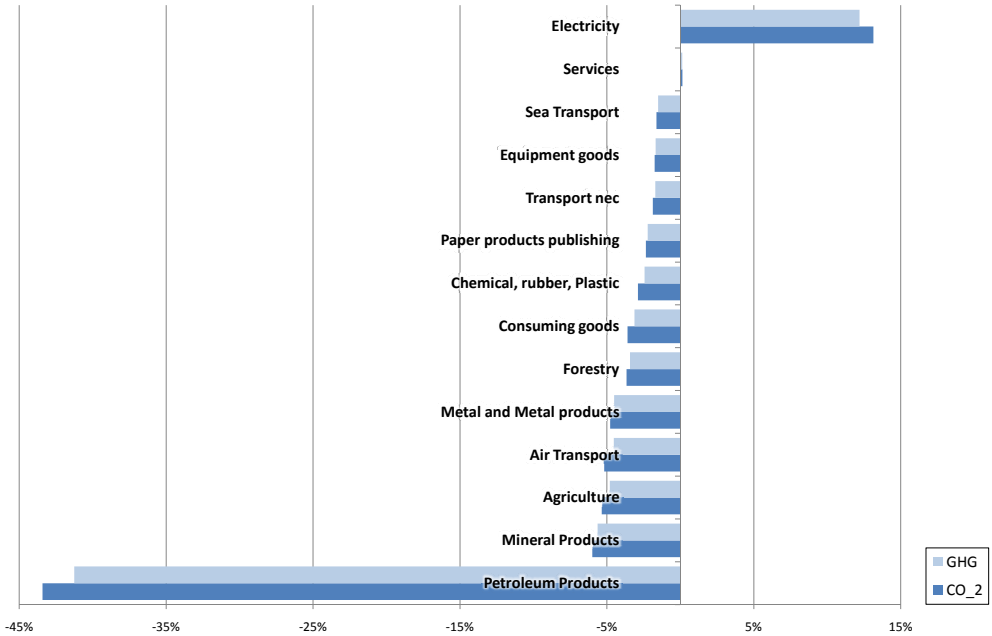

Figure 1.7: Variation of production in 2050 relative to baseline

occurs mainly because of an increase in SF_6 (sulfur hexafluoride) emissions from electric power systems.

From an international perspective, we can confirm that Swiss policies, regardless of how stringent they are, have a very limited impact on the economies of the rest of the world, in particular when other regions are not undertaking GHG emissions abatement and no emission trading is envisaged. Nevertheless, the implementations of GHG and CO_2 taxes in Switzerland influences the CHF/USD exchange rate and, as a consequence, slightly affects trade flows. The Swiss exchange rate increases by 0.7% to 1.8% with respect to the US dollar depending on the level of the tax.

Finally, the estimations confirm our initial assumption that the prices of energy would only vary slightly compared to the baseline due to the limited impact of Swiss energy demand on world prices.

1.6.5 Impacts on the residential sector

As we saw earlier, the implementation of emissions taxes has strong consequences on the residential sector. The bottom-up part of the coupled model shows, as presented in Figure 1.8, that the residential sector reacts to the introduction of

the taxes by a strong switch to electricity between 2020 and 2035. A constant tax of 156.5 USD/tCO_2eq would even have an earlier and stronger impact and would even trigger an almost CO_2 free residential sector.

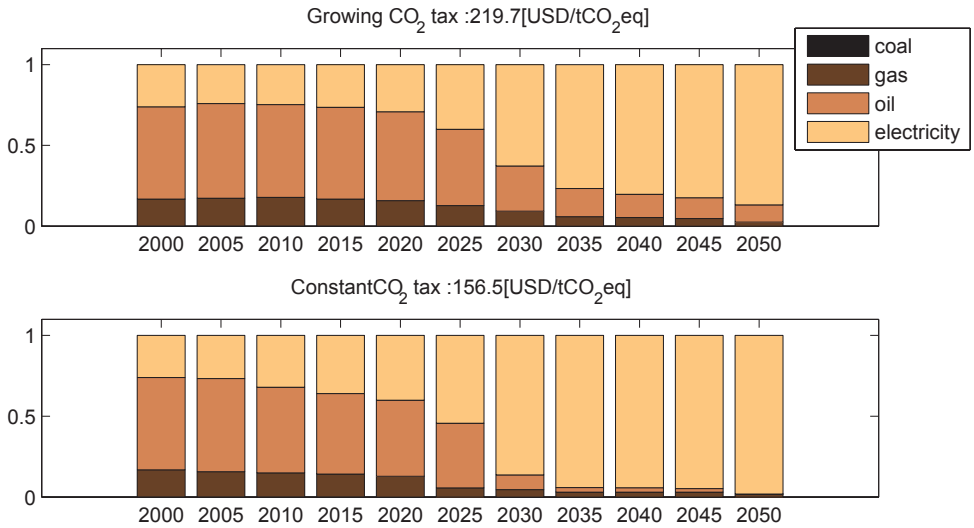

Figure 1.8: Residential fuel mix

Figure 1.9 presents the evolution of installed capacity of various room heating technologies following the implementation of and increasing GHG tax allowing the model to reach a 50% abatement by 2050. It clearly indicates that, in all building types, heat pumps will have a rapidly growing share and, as of 2030, be the dominant technology used for room heating. This is due to the fact that heat pumps have a high energy efficiency and that they only consume electricity, which is, to a large extent in Switzerland, not produced from fossil fuels. Finally, the figure also shows that an important part of the final energy demand is met by installing energy saving technologies, in particular in new single family houses where almost a fourth of the energy is saved by using appropriate insulation and other energy efficiency standards.

1.7 Conclusions

This paper provides a new integrated approach to analyzing GHG mitigation policies in Switzerland which provides useful insights relevant for the forthcoming revision of the CO_2 law and the elaboration of the post 2012 climate policies. We

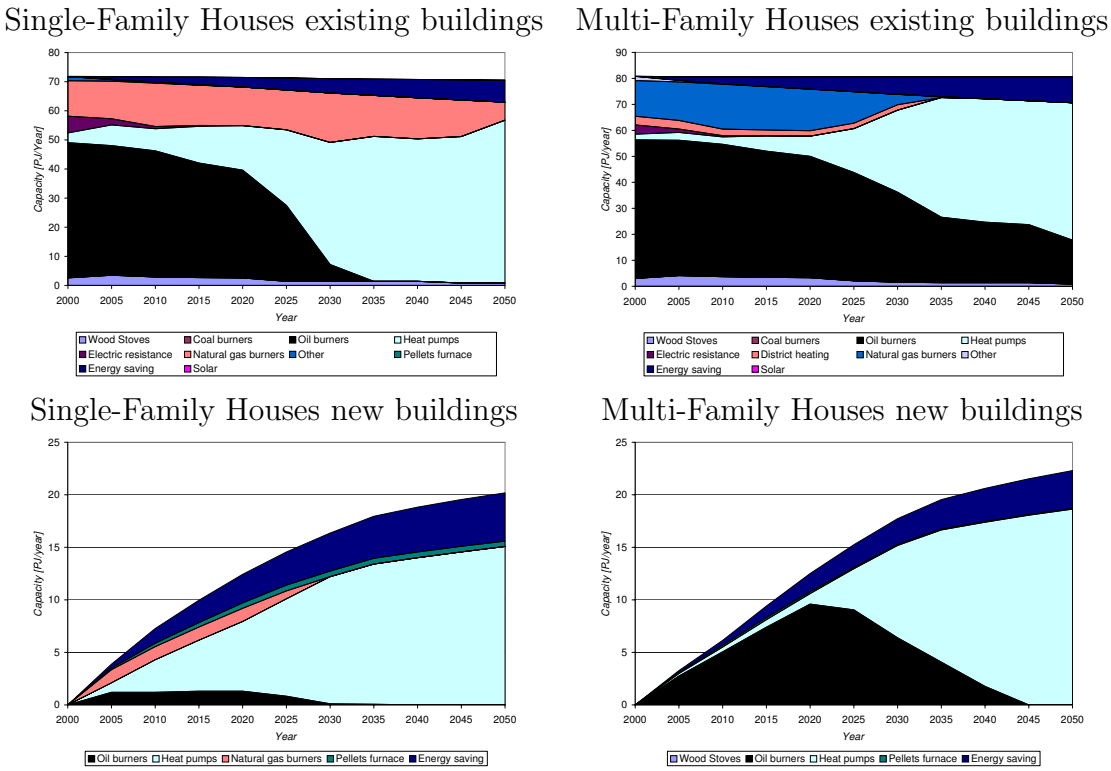

Figure 1.9: Installed capacity of room heating technologies

have focused this analysis on the residential sector which is expected to play a major role in future GHG abatement.

We have studied the impacts of CO_2 and GHG taxes as well as technical regulation applied to the residential sector. We have shown that the latter would not be sufficient to achieve major emissions reductions and loose their *raison d'être* when used in conjunction with emission taxes. This effect might be a little overestimated by the MARKAL-CHRES part of the coupled model, which assumes that consumers adopt purely optimizing behavior which takes into account investment, maintenance and usage prices of all technologies. Furthermore, this study confirms that GHG taxes are more effective than CO_2 taxes, without further jeopardizing the production of the economic sectors. A GHG tax reaching 201.6 USD/tCO_2eq in 2050 would yield a 50% reduction in GHG emissions relative to 1990 and would lower Swiss GDP by approximately 0.4% compared to the baseline. Such a tax would imply, for example, that the prices of light fuel oil used in the residential sector would increase annually by 0.012 USD_{2000} per liter.

Finally, this paper also shows that with high emissions taxes, transportation becomes the principal emitter of GHG. This is in line with a proposal for a Swiss energy policy by ETHZ (2008), which states that emissions should be reduced to 1 tCO_2 per capita by 2100, a potentially sufficient condition to ensure a sustainable global temperature increase arround 2°C if applied globally in a contraction and convergence framework, and that those emissions would be mainly be due to long distance transport . In the settings of this paper, the transportation sector remains a big emitter due to the rigidities in the model, which somehow reflects the lack of clean alternative technologies, but also to the fact that the price of petroleum products used for transport already includes high taxes and, therefore, the relative change in price is much lower than in the residential sector.

This research is further developed in the next chapter by an analysis of policies aiming at a CO_2 neutral Switzerland, as well as their consequences. As assumed by the Federal Council, this could be done investing a part of the tax revenue in the purchase of foreign CO_2 certificates. Having in mind that the marginal abatement costs in Switzerland are very high, the purchase of certificates would significantly lower the costs of abatement. Some amendments to the model could enable a global or regional carbon market and, once abatement strategies in all regions would be defined, will allow the assessment of the international price of CO_2 certificates. Once climate policies will be internationally introduced in the models, energy prices and demands will vary substantially. The coupling framework must therefore also be amended to allow feedbacks from the top-down to the bottom-up model. Furthermore, the variation of the investment costs following the implementation of the policies will also be aligned between both models in order to render a more realistic framework with regard to the macroeconomic consequences of the investments in the residential sector. Finally, a more detailed modeling of the private transportation sector, using another energy use model, would allow to take into account the realistic hypothesis that, before 2050, energies other that petroleum products could represent an important share in the private transportation fuel mix. These additional substitution potentials should allow reaching the emission targets with lower taxes than those presented in this chapter[1].

[1] Chapter 3 presents an application of the additional coupling of a bottom-up transportation model with GEMINI-E3.

Acknowledgements

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Chapter 2

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

This chapter is a slightly amended version of the paper *"Sustainability, neutrality and beyond in the framework of Swiss post-2012 climate policy"* written by André Sceia, Juan-Carlos Altamirano-Cabrera, Thorsten F. Schulz and Marc Vielle (Sceia et al., 2009a), a NCCR working paper also under revision at the peer-reviewed Journal of Policy Modeling.

Abstract

Switzerland, like many developed countries, faces 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 give Switzerland a first-mover advantage 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

2.1 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.

It is expected that major developed countries (as important GHG emitters) undertake a large part of emission reductions. This will leave little scope for small developed countries, such as Switzerland, to engage significantly in future global climate policy. However, as Thalmann (2007) points out, there are various reasons, both ethical and economic, for a small country like Switzerland to take part in the global effort to fight climate change. Among those, the positive effect on welfare of the reduction of fossil fuels imports is certainly valid for many other big and small countries across the globe. Furthermore, as the Swiss economy is, to a great extend, based on services, the largest share of GHG emissions comes from the residential and transport sectors. Having in mind that the transport sector has low elasticities and high marginal abatement costs, we think that it is sensible to put special emphasis on the residential sector, as it presents the most affordable abatement possibilities using existing technologies.

The objective of this paper is to assess the economic consequences of a number of ambitious climate polices on the Swiss economy. Policies combine the implementation of a linearly increasing Swiss GHG emissions tax, which triggers domestic abatement, with the purchase of GHG emissions certificates on a global market, which allows compensating emissions. The assumption of a linear increase of the tax is based on the current Swiss CO_2 law, in which the tax is

increased over time if objectives are not met. In view of the size of Switzerland, the price of the certificates is assumed to be influenced mainly 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 the purchase of foreign GHG emissions certificates.

In this chapter, we use a coupled top-down bottom-up model to precisely represent the technological specificities of the Swiss residential sector[1] 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, Böhringer (1998); Drouet et al. (2005b); 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. 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 a more complete and realistic assessment of the macro- and microeconomic impacts of a set of climate policy measures. Finally, until now, the only coupling papers specifically targeted to the Swiss residential sector are Drouet et al. (2005b) and Sceia et al. (2008)[2]. Drouet et al. (2005b) 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 an earlier version of the model that we use in this paper and showed that the coupling of a bottom-up model to a CGE provides lower estimations of marginal abatement costs for high

[1] In 2005, the residential sector represented 22.3% of total GHG emissions.
[2] A slightly amended version of this paper is presented in chapter 1.

abatement levels. Due to its rich technological representation, the bottom-up model removes the necessity to introduce arbitrary backstop technologies to limit the marginal abatement costs, which tend to be exponential in CGE models. We made various improvement to the coupling procedure, the models and 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 Swiss policies becomes important, but getting on the track of sustainability could be affordable with an increasing GHG tax reaching around 140 USD_{2001}/tCO_2eq in 2050.

The chapter is organized as follows: section 2.2 presents the models and the methodology, section 2.3 the policy scenarios, section 2.4 the results and section 2.5 concludes.

2.2 Models and methodology

2.2.1 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[3]. 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 Munson, 2000; Ferris and Pang, 1997). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-6 database (Di-

[3]The complete GEMINI-E3 represents the world economy in 28 regions (including Switzerland) and 18 sectors (see Table B.1 in appendix B.3 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).

[4]Refers to the 27 European Union member states as of 2008.

[5]Includes other European countries, Russia and the rest of the Former Soviet Union excluding Baltic states.

maranan, 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 the 2001 input-output table devised at the Swiss Federal Institute of Technology (ETH) in Zürich (Nathani et al., 2006), which we transformed into 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).

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 net welfare gains 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 calibrate and the couple 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 2.1. The σ^x

refer to the elasticity parameter of each node. Plain numbers in the figure refer to economic sectors as presented in appendix B.3 Table B.1, 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.

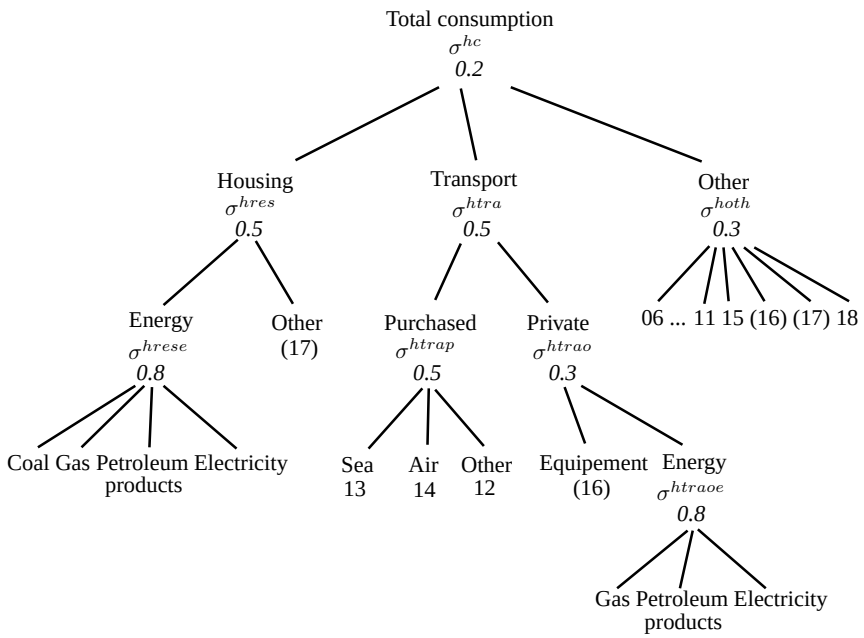

Figure 2.1: Structure of the households' nested CES utility function

We have also introduced an emission certificates market that allows 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 increasing GHG tax, independent from the global price of certificates, to control the level of domestic abatement.

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 or insufficient mitigation efforts are 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. Furthermore, we do not account for other ancillary benefits of climate policies

such as the reduction of local air pollution. As a consequence, mitigation costs, when analyzed independently from climate change damages, adaption costs and other positive effects, are particularly relevant to compare policies with similar objective.

Measuring the mitigation 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

$$WG_t = \Delta R_t - CVI_t, \tag{2.1}$$

where ΔR is the variation of income, mainly due to transfers through international trade. Moreover, we are interested in separating the trade effect from the direct consequences of the policy, including the purchase of foreign emissions certificates. Therefore, the net welfare gains (NWG_t) can be expressed as

$$NWG_t = WG_t - GTT_t, \tag{2.2}$$

where GTT is the gains or losses of the terms of trade. Assuming that trade balances are indeed balanced at each period and for each region, the GTT can be calculated as follows,

$$GTT_t = \sum_i (X^0_{i,t} \cdot \Delta P^X_{i,t} - M^0_{i,t} \cdot \Delta P^M_{i,t}), \tag{2.3}$$

where, for sector i at period t, $X^0_{i,t}$ represents baseline exports, $M^0_{i,t}$ are the baseline imports, $\Delta P^X_{i,t}$ is the export price variation between the baseline and the scenario and $\Delta P^M_{i,t}$ is the import price variation. The sums of GTT 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 net welfare gains.

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.

2.2.2 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 13 energy demand segments (see appendix B.3 Table B.2); 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 de-

mand. 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 specifically aimed at 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).

2.2.3 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} per barrel (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 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/m^2year) multiplied by REA (Mio m^2). The Swiss Federal Office of Energy provides estimates of the REA until 2035. We extrapolate values until 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 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 arround the average of studies published since the SRES (IPCC, 2007b). Global GHG emissions reach 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 2.4). 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.

2.2.4 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 an important share of the total GHG emissions and seems to allow important abatement possibilities at reasonable costs (see chapter 1). In general, coupling top-down with bottom-up models allows benefiting 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.

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 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 targets 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 is sufficient to purchase enough certificates on the global carbon market to achieve the total emission target. If both domestic and total targets are defined, the coupling procedure sets the tax so that domestic target are achieved and the tax revenue is sufficient to purchase the remaining 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 2.2 presents the coupling schema. The GHG 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}^{hrese}) 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.

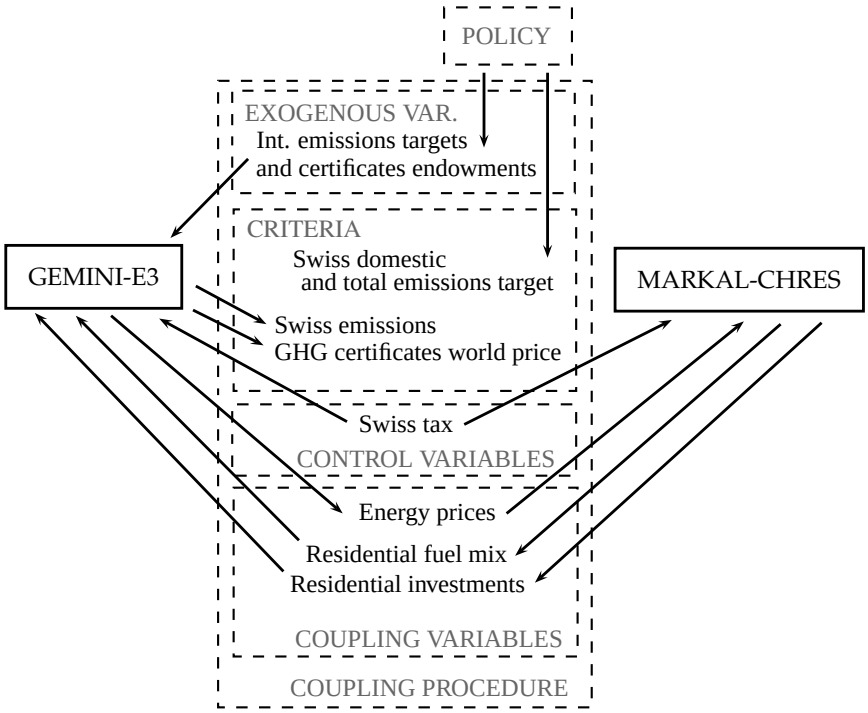

Figure 2.2: Coupling structure

The coupling module has 2 levels. The first level looks for a tax that will ensure reaching emission targets, 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 B.1).

2.3 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 economic, equity and development issues. Considering the latter, 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

international agreement targets for the next commitment period?

2.3.1 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. van Vuuren et al. (2006) and Chapter 1), to focus on policies targeting abatement of all GHGs because this results in lower abatement costs. Table 2.1 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.

Table 2.1: 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

The so-called "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. It supposes an active participation of the majority of the world, including the major emerging economies as of 2030. The "mid" and "low" scenarios consider alternatives where climate negotiations would lead to less stringent emission targets, in particular for the DCS. Our three scenario belong respectively to the categories III to V of the IPCC scenarios (IPCC, 2007b). We consider that scenarios of the category I and II, where global GHG emissions should peak before 2015 or 2020, are unrealistic in the light of current

developments of climate change negotiations, in particular, the lack of meaningful commitments from developing countries.

2.3.2 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 egalitarian 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 an increasing 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 and the leftover, which occurs only when a minimum domestic abatement is imposed, is redistributed to households through a lump sum transfer. Figure 2.3 shows the case where no minimal domestic emissions target is set and where the tax is set solely to allow 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.

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

- First, the "50%" scenario 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 tCO_2/cap by 2100. We consider, as simplifying as-

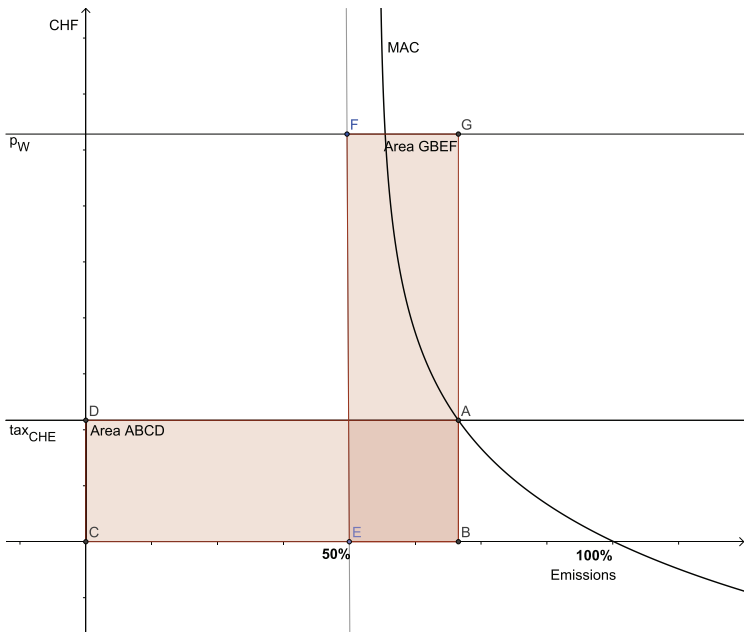

Figure 2.3: Tax revenue used to purchase GHG certificates for 50% total abatement

sumption and to be in line with the time horizon of the model, that this translates to 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 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 revenue

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 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+".

2.4 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 abatement effort and the evolution of the sector from a technical perspective.

2.4.1 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 $GtCO_2eq$, only 2% higher than 2001 levels. Figure 2.4 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 CO_2. 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 USD_{2001}/tCO_2eq.

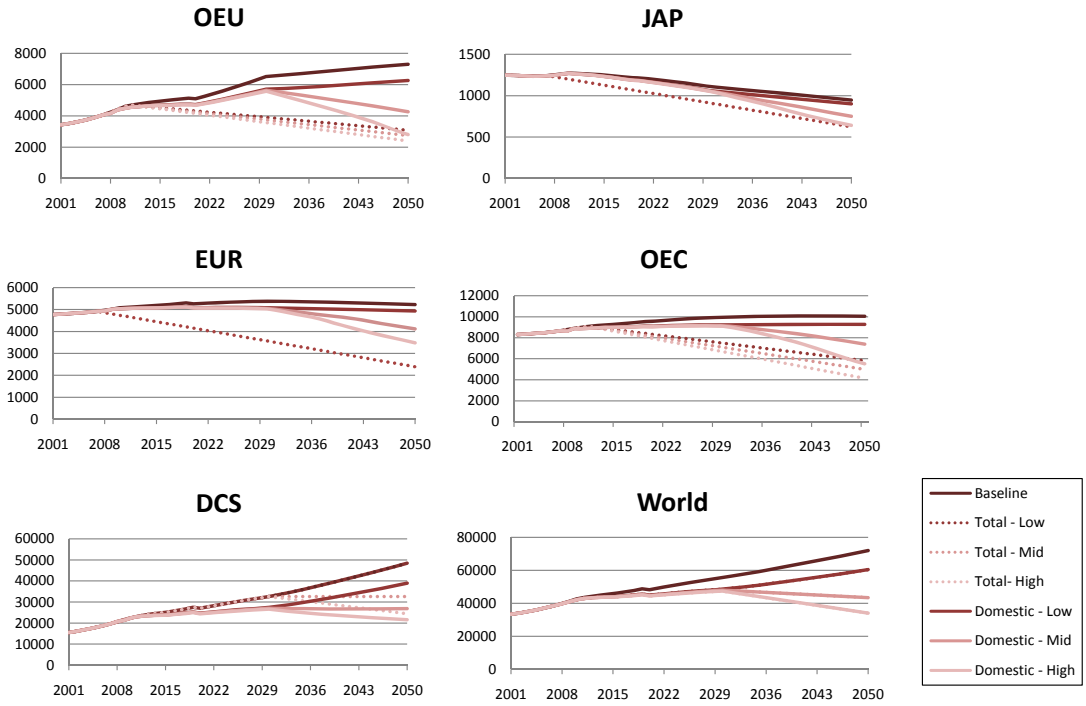

Figure 2.4: International GHG emissions ($MtCO_2eq$)

Table 2.2 presents an aggregated welfare decomposition for the period 2008-2050 and it shows the impact of the three scenarios on the world economy. The total welfare, i.e. the consumer surplus calculated on the basis of the CVI, is decomposed into the gains and losses of the terms of trade (GTT) and the net welfare gains due to the policy (see equation 2.2). 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

Table 2.2: Welfare decomposition (in % of final households consumption)[a]

Scenarios	Region	WG[b]	GTT[c]	NWG[d]
Low	OEU	-0.24	0.13	-0.37
	JAP	-0.03	-0.01	-0.02
	EUR	-0.08	-0.02	-0.06
	OEC	-0.07	-0.03	-0.03
	DCS	0.11	0.06	0.05
	World	0.00	-	0.00
Mid	OEU	-0.24	0.28	-0.96
	JAP	-0.06	-0.03	-0.03
	EUR	-0.18	-0.05	-0.13
	OEC	-0.17	-0.08	-0.09
	DCS	0.21	0.14	0.07
	World	-0.03	-	-0.03
High	OEU	-2.72	-0.10	-2.62
	JAP	-0.06	-0.01	-0.05
	EUR	-0.33	-0.04	-0.29
	OEC	-0.38	-0.12	-0.26
	DCS	0.32	0.22	0.11
	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 gains
[c] Gains and losses of the terms of trade
[d] Net welfare gains

as well as the gains in the terms of trade. Concerning the other regions, JAP has limited losses in consumer surplus because in the baseline their emissions already decline by almost 25%; a consequence of slow GDP growth. EUR and OEC face similar total welfare losses, ranging from of 0.07% of aggregated total households consumption in the "low" scenario to 0.38% in the "high" scenario. In view of these results, it appears that even the "high" scenarios would be achievable at reasonable costs and allows DCS to maintain the growth required to their economic development. We compare these results with those for Switzerland in the next section.

2.4.2 Swiss economy

Table 2.3 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.

Table 2.3: Summary results for Switzerland

	Scenarios	Abatement in 2050[a]		Swiss	GHG	2008-2050[d]		
World	Switzerland	Domestic	Total	tax[b]	price[c]	WG	GTT	NWG
Low	50%	-28	-50	1.2	3.8	0.02	-0.01	0.03
	sustainable	-28	-75	2.5	3.8	0.01	-0.01	0.02
	neutral	-28	-100	3.8	3.8	0.01	-0.01	0.01
	zero-footprint	-30	-180	8.3	3.9	-0.01	-0.01	-0.01
	50%+	-50	-50	103.3	3.8	0.22	0.29	-0.07
	sustainable+	-50	-75	103.2	3.8	0.21	0.29	-0.08
	neutral+	-50	-100	103.2	3.8	0.20	0.28	-0.08
	zero-footprint+	-50	-180	103.1	3.8	0.17	0.27	-0.10
Mid	50%	-32	-50	9.4	34.6	0.00	-0.02	0.01
	sustainable	-36	-75	21.0	34.7	0.01	0.02	-0.01
	neutral	-40	-100	34.8	34.8	0.01	0.05	-0.03
	zero-footprint	-50	-180	90.6	35.1	0.06	0.20	-0.14
	50%+	-50	-50	101.0	34.6	0.19	0.26	-0.07
	sustainable+	-50	-75	100.8	34.6	0.17	0.25	-0.08
	neutral+	-50	-100	100.7	34.7	0.14	0.24	-0.10
	zero-footprint+	-50	-180	100.0	35.1	0.07	0.21	-0.14
High	50%	-35	-50	67.5	289.4	0.10	0.15	-0.05
	sustainable (+)	-50	-75	144.2	289.8	0.12	0.30	-0.18
	neutral (+)	-54	-100	290.6	290.6	0.10	0.43	-0.33
	zero-footprint (+)	-63	-180	926.5	293.6	-0.23	0.88	-1.10
	50%+	-50	-50	156.7	288.8	0.21	0.35	-0.14

[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 in Table 2.3 show that, in general, international climate policies have a strong influence on the effect of domestic GHG taxes. In the "low" and

"mid" scenarios, regardless of the implemented Swiss policy, the NWG caused by the climate policy is not larger than -0.14%. 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 NWG is -1.1% - not surprisingly as the level of domestic GHG tax in 2050 exceeds 900 USD_{2001}/tCO2eq. Despite the decreasing NWG, 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 NWG. 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[6], 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 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 (in 2050) and allowing 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. Further-

[6] 100% of fossil fuels used in Switzerland are imported.

more, 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 does Japan suffer smaller welfare losses than Switzerland under some of the international abatement schemes.

We further observe that when there is a 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/tCO_2eq. 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/tCO_2eq, the gains in the terms of trade resulting from the higher tax result in 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/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 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 and requires a lower tax, i.e. 144 USD/tCO_2eq, to achieve the same domestic target. Figure 2.5 schematically represents the effect of a translation of the marginal abatement costs (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 a 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 a 50% domestic abatement decrease when the total abatement requirements increase.

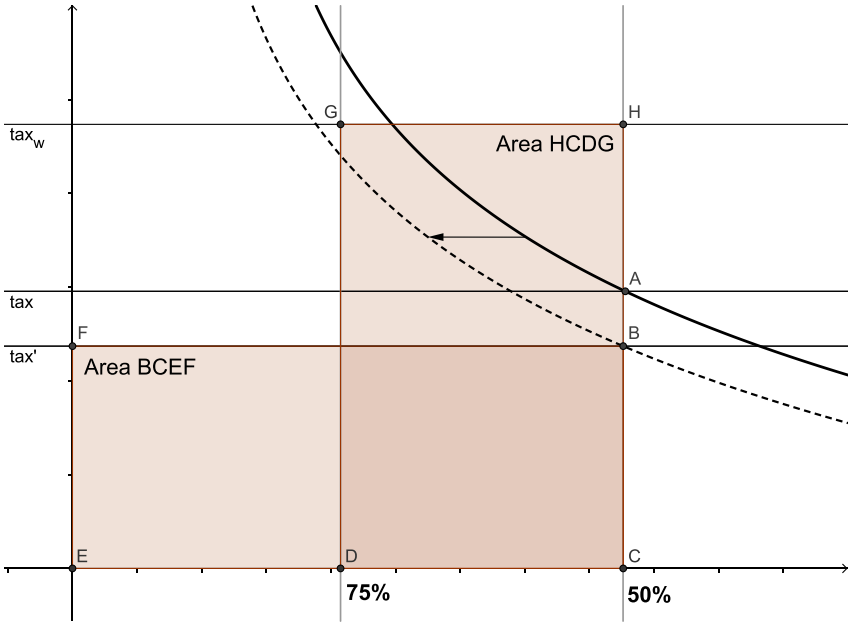

Figure 2.5: Translation of the MAC curve due to activity reduction

On the production side, there are no surprises for the two energy sectors active in Switzerland. Figure 2.6 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,

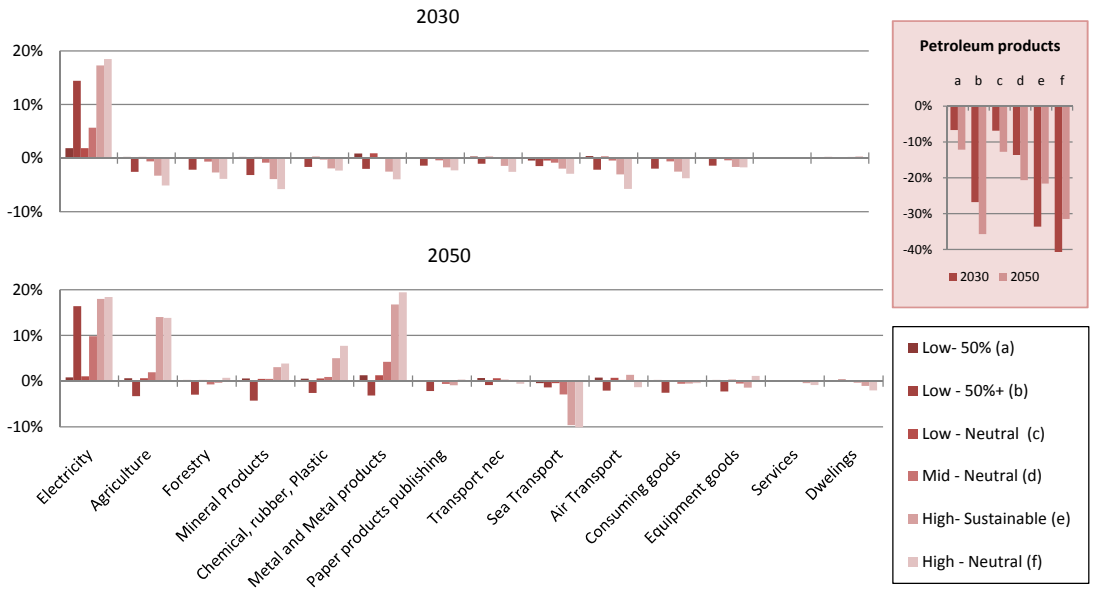

Figure 2.6: Sectoral production change due to the policy scenarios

the transport sector faces an increase in energy prices of approximately 70% but nevertheless, in view of the low substitutability of transport to other inputs[7], 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 (this is done in Chapter 3).

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 in 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 2.7 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 partic-

[7]The elasticity is set to 0.2.

ular 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 dependance 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.

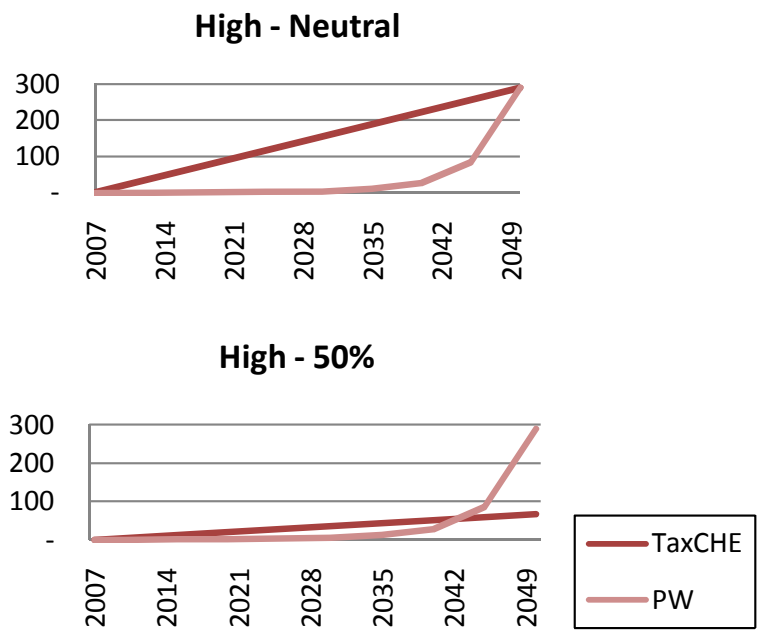

Figure 2.7: Swiss tax vs international price of certificates [USD_{2001}/CO_2eq]

2.4.3 Swiss residential sector

Emissions

Figure 2.8 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/tCO_2eq ("mid" - "neutral"), and does the major part of it when the tax gets close to 100 USD/tCO_2eq ("low" - "50%+")[8]. In the high scenarios, the residential sector stops emitting CO_2 as early as 2030, switching to technologies using electricity instead of fossil fuels.

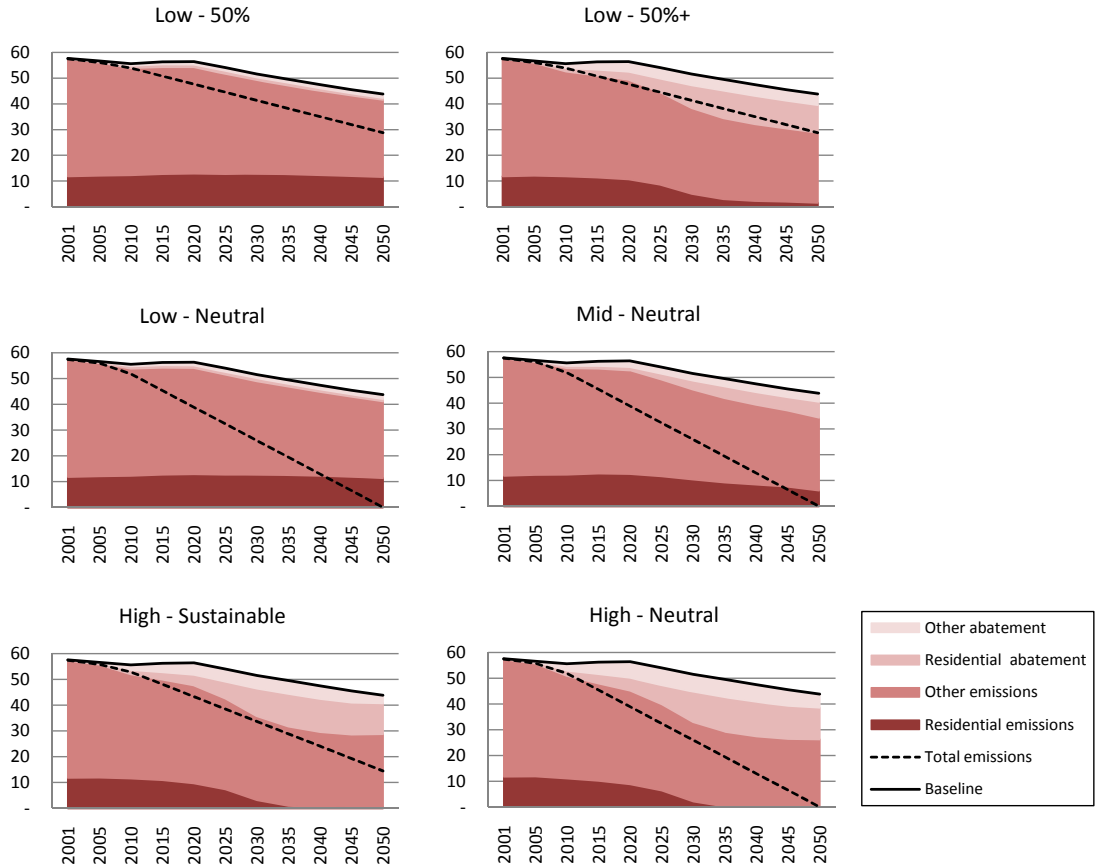

Figure 2.8: Contribution to the abatement of the residential sector [MtCO_2eq]

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 subsector, which in 2000 accounted by far for the largest share of residential energy

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

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.

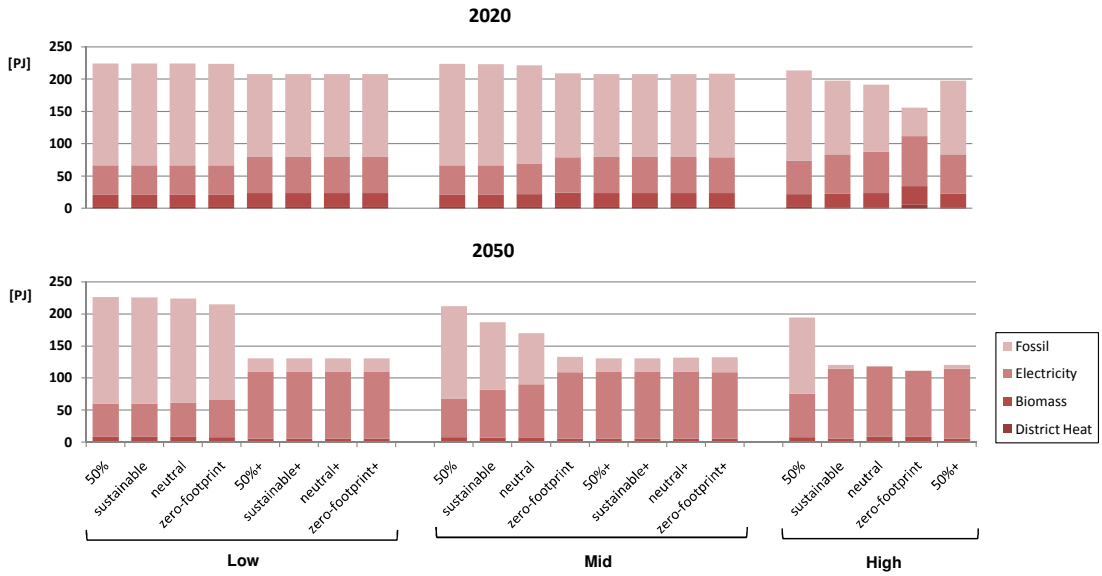

Figure 2.9: Fuel consumption in the residential sector

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 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 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.

Table 2.4: 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

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 declines further to about 130 PJ in 2050. A large share of this reduction occurs in the residential heating sub-sector, where energy consumption is halved to about 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 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 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 or triple-glazed window insulation with a thermal transmission coefficient of 1 W/m^2K [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.

[9] Watt per square meter-kelvin.

2.5 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 2tCO_2eq/cap while ensuring at least 50% domestic abatement through the implementation of a domestic increasing GHG tax reaching 144 USD_{2001}/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 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 coupling procedure for other parts of the economy, e.g. private transportation[10], 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

[10]Chapter 3 presents an application of the additional coupling of a bottom-up transportation model with GEMINI-E3.

additional insights by identifying specific technologies and enhances the overall modeling framework by taking into account the fact that technological changes are costly and cannot be undertaken overnight.

Acknowledgements

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Chapter 3

Assessment of acceptable Swiss post-2012 climate policies with a hybrid model

This chapter is a slightly amended version of the paper *"Assessment of acceptable Swiss post-2012 climate policies"* written by André Sceia, Juan-Carlos Altamirano-Cabrera, Marc Vielle and Nicolas Weidmann (Sceia et al., 2009b), an NCCR working paper also submitted to the peer-reviewed journal Climate Policy. An earlier version of this paper was used by André Sceia, Philippe Thalmann and Marc Vielle to produce the report *"Assessment of the economic impacts of the revision of the Swiss CO2 law with a hybrid model"* for the Federal Office for the Environment (FOEN)(Sceia et al., 2009c).

Abstract

In the framework of the revision of the Swiss CO_2-Law and in view of the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change, the Federal Office for the Environment (FOEN) has proposed a set of instruments and two levels of abatement to define the Swiss climate policy for the post-2012 period. The proposed policies are the results of a consultation procedure that took place in the summer of 2009 and has allowed major stakeholders

and lobbies to defend their interests. Using an hybrid model, we evaluated two proposed scenarios at the 2030 horizon and find important disparities in the prices of carbon faced by the different economic sectors and higher welfare costs than those that would be triggered by a uniform carbon tax.

Keywords: Climate policy, Environmental taxation, Hybrid modeling, Transport, Residential, Welfare economics

3.1 Introduction

In the framework of the revision of the Swiss CO_2-Law and in view of the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change, the Federal Office for the Environment (FOEN) has proposed a set of instruments and two levels of abatement to define the Swiss climate policy for the post-2012 period. The proposed policies are the results of a consultation procedure that took place in the summer of 2009 and has allowed major stakeholders and lobbies to defend their interests. As for the European Union, a first scenario is envisaged for the case where the climate negotiations would reach a moderate global abatement and a second more stringent scenario in the case where the rest of the world would commit to strong emissions reductions.

In Switzerland, as in many other OECD countries, transportation and housing are responsible for the major part of greenhouse gas (GHG) emissions. With this in mind and taking into account the views expressed during the consultation procedure on the revision of the Swiss CO_2-Law, the FOEN has devised policies composed of various instruments and sectoral targets. A detailed description of the envisaged targets and instruments is presented in section 3.4.

In order to adequately evaluate the future Swiss climate policies, to model all the envisaged instruments and to consider the influence of the choices that will be made in the rest of the worlds, we have coupled the GEMINI-E3 model, a worldwide CGE model, with MARKAL-CHRES and MARKAL-CHTRA, two energy models describing respectively the Swiss residential and transportation sectors. This chapter continues the work undertaken in chapter 2 by proposing a new coupling approach and an integrated assessment of the climate policies currently under discussion.

The harmonization or the integration of top-down and bottom-up models has been extensively studied but remains at the top of the agenda for researchers dealing with energy, environment and economy issues as no ideal solution has been recognized yet. Two main methods have been used to tackle the issue. They are commonly refereed to as soft-link and hard-link methods. While the first keeps top-down and bottom up models separate, the later integrates both in a single model. The application of those methods is not uniform either and different models are linked or integrated in different ways. We use a soft-link method that is different from those found in other studies. Drouet et al. (2005b) use a MARKAL model of the Swiss residential sector to complement a CGE model in which the residential sector has been removed. We keep GEMINI-E3 and both MARKAL models in their complete from and dynamically align them. Contrary to Schäfer and Jacoby (2005), we link the models both in the calibration and simulation phases. With regard to the hard-link method, most studies only integrate a reduced form of one of the models types. Examples include MARKAL-macro models, as used by Strachan and Kannan (2008), that integrate a simplified economic module in a bottom-up framework or CGE models complemented by a technological representation of a specific sector such as electricity generation (Wing, 2006) or specific industrial processes (Murphy et al., 2007; Schumacher and Sands, 2007). More complete integrations in a single modeling framework have been proposed by Frei et al. (2003), Böhringer and Rutherford (2008) or Böhringer and Rutherford (2009) but are so far only implemented with stylized models.

This paper is organized as follows: section 3.2 presents the models and the coupling methodology, section 3.3 presents the baseline scenario, sections 3.4 and 3.5 present the policy scenarios and their respective results and section 3.6 concludes.

3.2 Methodology

3.2.1 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]. For Switzerland, we extend the number of sectors to 29 in order to precisely present the transportation sector. The sectors replacing the original "transport nec", "sea transport" and "air transport" are presented in table 3.1. We define 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 complete 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 use data from the 2001 input-output table devised at the Swiss Federal Institute of Technology (ETH) in Zürich (Nathani et al., 2006) as well as the transportation disaggregation performed in Infras (2006) and transform it to the GEMINI-E3 format (Sceia et al., 2009a). Data on emissions and abatement costs for non CO_2 GHG comes 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), to analyze the behavior of Russia with regard to the ratification process of the Kyoto Protocol (Bernard et al., 2003), to assess the costs of implementation of the Kyoto protocol in Switzerland with and without international emissions trading (Bernard et al., 2005) and to assess the effects of an increase of oil prices on global GHG emissions (Vielle and Viguier, 2007).

[1]The complete GEMINI-E3 represents the world economy in 28 regions (including Switzerland) and 18 sectors (see table C.1 in appendix C.1 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.

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 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 are also 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 calibrate and couple GEMINI-E3 with MARKAL-CHRES and MARKAL-CHTRA, we have replaced the Stone-Geary utility function by a nested constant elasticity of substitution (CES) function and modified the existing CES production function. The nesting structures are presented in figures C.2 and C.1. The complete and aggregated GEMINI-E3 dimensions are presented in appendix C.1 table C.1.

We have also included an international emission certificates market to model a global cap and trade system. Each region receives annually a free endowment of emission certificates, equal to the emission policy target. Moreover, in Switzerland, we have implemented a tax on heating fuels, a levy on transport fuels aimed at financing the purchase of foreign emissions certificates as well as an Emissions Trading Scheme (ETS) for energy intensive sectors (not linked to the global certificates market).

New transportation sectors

In order to better represent the Swiss transport sector in GEMINI-E3 and allow the coupling with a transport energy model for Switzerland, we use a disaggregation of the three original transport sectors (land, air and maritime) into 14 sectors (see table 3.1). The disaggregation affects two of the original sectors, i.e. "transport nec" (12) and "services" (17). The numbering of the new sectors allows identifying how the new transport sectors were originally aggregated.

Table 3.1: Transport sectors

Code	Transport sectors	Code	Transport sectors
12a	Rail infrastructure	14	Air transport
12b	Rail passenger transport	17d	Road infrastructure
12c	Rail goods transport	12e	Road commercial passenger transport
12d	Other public transport	12f	Road goods transport
13	Water transport	12g	Road goods own transport
17b	Water transport infrastructure	12h	Pipeline
17c	Air transport infrastructure	17e	Other transport help, support and intermediaries

Infrastructure This version of the model specifically describes the various transport infrastructures (roads, railway lines, ports and canals as well as airports) as specific economic sectors. This differentiation allows, in particular, adequate accounting of the use of road infrastructure, which, in other studies (e.g. Paltsev et al., 2004), is paid through fuel taxes.

Own transport Numerous companies perform a part or all of their transport on their own account, i.e. without calling upon services of transport companies. In a standard input-output matrix, this activity is accounted as an intermediate input from a sector to itself. The own transport activity also requires specific inputs (e.g. vehicles and fuel), which are traditionally spread across the sectors using them. To the contrary, the transport disaggregation we use represents the own transport as a separate sector and, therefore, allows an adequate modeling of the substitution possibilities between purchased and own transport services.

International trade and transport Since we have a disaggregated representation of the transport sectors only in Switzerland, we need a special procedure to link the exports and imports of those sectors with the rest of the international trade which is at a more aggregated level. Furthermore, the model explicitly calculates the transport margins related to the international trade and allocates them to the adequate transport sectors. We have modified the equations related to international trade and international transport margins, allowing the disaggregation of imports and trade margins and the aggregation of exports.

3.2.2 MARKAL-CHTRA & MARKAL-CHRES

MARKAL models are perfect-foresight bottom-up energy-system 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 energy flows over a given time horizon to satisfy given end-use energy demands.

The models MARKAL-CHRES and MARKAL-CHTRA are submodules of a larger Swiss MARKAL model (SMM) developed at the Paul Scherrer Institute (PSI) and previously used to analyze the Swiss 2000 Watt Society project (Schulz et al., 2008), among others. SMM describes the Swiss energy system including energy supply and end-use demand sectors with a detailed representation of important technologies and energy carriers. MARKAL-CHRES and MARKAL-CHTRA describe only the Swiss residential and transport sectors, respectively.

Both MARKAL-CHRES and MARKAL-CHTRA contain numerous technology options differing in their most important characteristics such as (type of input fuels, investment costs, operating and maintenance costs, lifetime, efficiency, time of introduction into the market, capacity growth rates, and emissions). These characteristics are described by time dependent and time independent data parameters. In transport this variety of technology options is mainly represented in the car and truck sectors. In the residential building sector on the other hand the model contains a large set of energy saving options such as wall insulation, and glazing of windows.

Base year (2000) energy demand in MARKAL-CHRES and MARKAL-CHTRA is calibrated to the data of the International Energy Agency (IEA) and Swiss statistics (Swiss Federal Office of Energy). The models have a time horizon from 2000 until 2050, divided into eleven time steps each representing a time period with a duration of five years. MARKAL-CHRES and MARKAL-CHTRA include respectively 13 and 14 energy demand segments (see appendix C.1 table C.3 and C.4) and use a 3.5% discount rate (Amstalden et al., 2007). For a more detailed description of the technologies used in the MARKAL models,

see (Schulz, 2007).

Since MARKAL-CHRES and MARKAL-CHTRA represent only energy end-use in the residential and transport sectors, information on the cost and availability of the fuels used by these sectors (such as coal, oil, diesel, gasoline, gas, electricity, wood, pellets and district heat) need to be provided to the models exogenously. In the analysis presented here, the evolution of energy prices are calculated on the basis of GEMINI-E3 (see section 3.2.3).

3.2.3 Coupling

Compared to chapters 1 and 2, the coupling procedure linking the models has been amended to let GEMINI-E3 calculate taxes according to given emissions profiles. The models are run alternatively while the coupling variables are exchanged between the models, as shown in figure 3.1, until a defined threshold on the variation of the taxes is reached. The coupling procedure also takes into account a building improvement program which is paid by a part of the revenue of the CO_2 tax on heating fuels.

Through the exchange of the coupling variables, the coupling procedure ensures the link between the three models. The coupling variables are the fuel mixes of both residential and transportation sectors, the investments in those sectors, the energy prices, taxes and the transport demands.

As in chapter 2, the prices of energies from GEMINI-E3 are used to control the price variations in the MARKAL models. Moreover, the fuel mixes and investments simulated by the MARKAL models are used to control the energy uses and spending in equipment and services in GEMINI-E3, through the dynamic updating of efficiency parameters in the production and consumption CES functions. On top of that, in order to allow an adequate modeling of the substitution between the various transport sectors, the demand segments in the MARKAL-CHTRA model could not be assumed to be independent as in the case of the residential sector. Indeed, if it is reasonable to assume that, in Switzerland, the demand of the residential energy services was not significantly affected by the introduction of climate policies. However, the same does not hold in the transportation sectors in view of the possible modal shift. Therefore, the evolution of the production of the various transportation sectors in GEMINI-E3 is used to

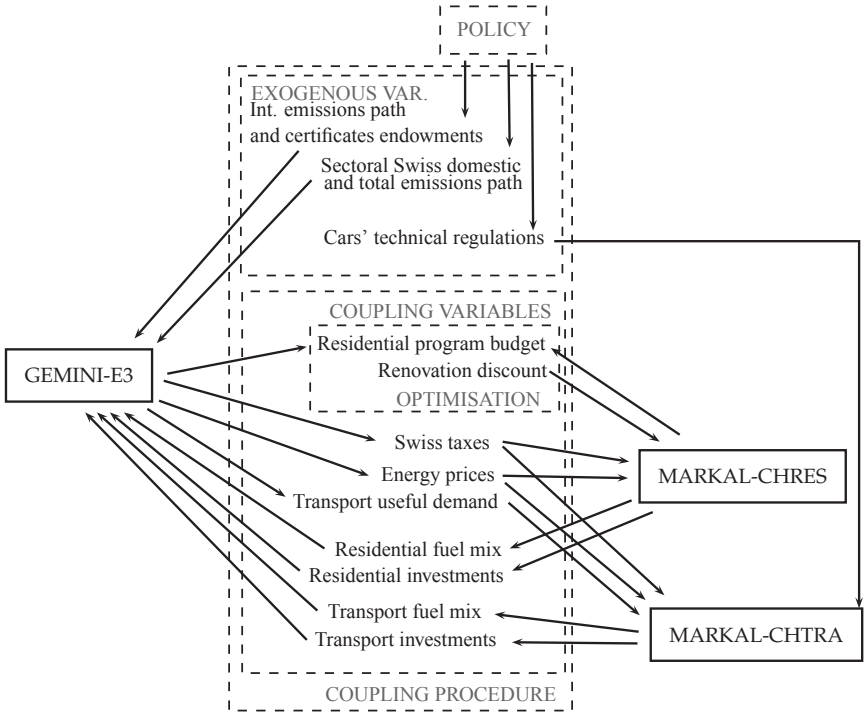

Figure 3.1: Coupling schema

control the variation of the transport demand segments in MARKAL-CHTRA.

In view of the different structures of GEMINI-E3 and MARKAL, in particular for the transport sector, we had to define the correspondence between the GEMINI-E3 sectors and the MARKAL-CHTRA demand segments (see table 3.2).

Similarly, the energy demand segments used in the MARKAL-CHTRA models do not match the energy sectors defined in GEMINI-E3 and therefore a correspondence has to be established (see table 3.3).

3.3 Baseline scenario

The GEMINI-E3 model with the disaggregated transportation sectors, once linked to the MARKAL-CHRES and MARKAL-CHTRA models and calibrated to Swiss GDP and population figures, calculates a baseline scenario until 2030. For Switzerland, the GDP growth rate is in line with the Secretariat of Economic Affairs (SECO) estimates and is equal to 1.2% per year, whereas for other regions, they

Table 3.2: Transportation sectors and links to the MARKAL-CHTRA segments

Code	GEMINI-E3 Sector	MARKAL demand segments
12a	Rail infrastructure	–
12b	Rail passenger transport	Rail-Passengers
12c	Rail goods transport	Rail-Freight
12d	Other public transport	–
13	Water transport	Domestic Internal Navigation, International Navigation
17b	Water transport infrastructure	–
17c	Air transport infrastructure	–
14	Air transport	Domestic Aviation, International Aviation
17d	Road infrastructure	–
12e	Road commercial passenger transport	Road Bus
12f	Road goods transport	Road Medium Trucks
12g	Road goods own transport	Road Medium Trucks
12h	Pipeline	–
17e	Other transport help, support and intermediaries	–
HC	Households	Road Auto, Road Two Wheels

mainly follow forecasts from Energy Information Administration (2008), whereby world annual growth amounts 2.8%.

The baseline oil prices are also a key assumption for the model. We use a smoothed series of historical prices and keep the oil prices at 50 USD_{2008}/bbl until 2020. The price of oil is then assumed to grow linearly to 100 USD_{2008}/bbl in 2050, thus reaching 66 USD_{2008}/bbl in 2030. For Switzerland, the calibration of the model with regard to the combustible fuels consumption is made assuming that temperatures will correspond to the average over the years 1970–1992.

In our baseline scenario, the world GHG emissions reach a little more than 55 $GtCO_2eq$ by 2030, which is in line with OECD (2008). Figure 3.2 presents the GHG emissions for each region until 2030.

Table 3.4 presents the variations of the Swiss baseline emissions for the transport, residential and emission trading system (ETS) sectors (Refined Petroleum, Electricity, Mineral Products, Chemical Rubber Plastic, Metal and Metal Prod-

Table 3.3: Fuels links

MARKAL-CHTRA		GEMINI-E3
AVG	Aviation Gasoline	04 Refined Petroleum
COA	Coal	01 Coal
DST	Diesel	04 Refined Petroleum
ELC	Electricity	05 Electricity
ETH	Ethanol	06 Agriculture[a]
GSL	Gasoline	04 Refined Petroleum
HDN	Hydrogen[b]	–
HFO	Heavy Fuel Oil	04 Refined Petroleum
JTK	Jet Kerosene	04 Refined Petroleum
LPG	Liquified Petroleum Gas	04 Refined Petroleum
MET	Methanol	03 Natural Gas
NGA	Natural Gas	03 Natural Gas

[a] This link holds for the energy prices but, in view of time constraints, the CES functions in the energy nests of GEMINI-E3 do not allow the use of agricultural products like ethanol as an energy. As a consequence and since the ethanol share is and remains marginal, we have added the ethanol share to the electricity sector, in order not to affect the Swiss CO_2 emissions.
[b] Not used in this version of the model

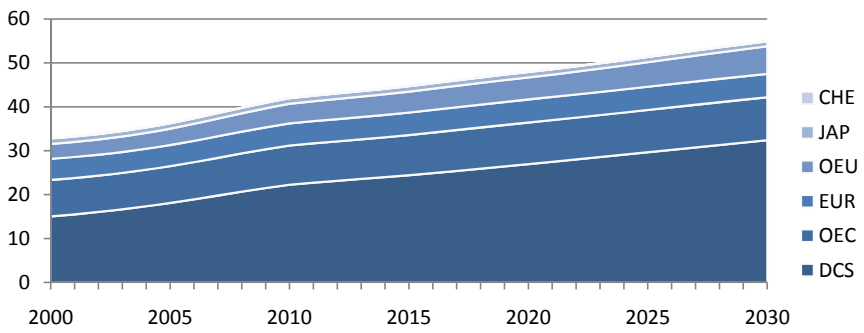

Figure 3.2: Baseline GHG emissions ($GtCO_2eq$)

ucts and Paper Products Publishing) as well as the emissions from air transport (national and international) and all other CO_2 emissions. It also presents the variation of all emissions which will be subject to the CO_2 tax on combustible fuels, i.e. those from the residential sector and those from the other sectors. Data on the variation of the other GHG are also presented in detail. On average, the Swiss

baseline GHG emissions will decrease annually by 0.6%. Note that this reduction is comparable to the one of Japan, which has a similar GDP growth (Energy Information Administration, 2008). The calibration of the baseline emissions is based on Swiss Federal Office of Energy (2007) Scenario I.A, which assumes the continuation of present climate policies and the construction of new nuclear power plants to replace those that will be phased out over the coming decades.

Table 3.4: Variation of the baseline GHG emissions (% of 1990)

	1990[a]	2020	2030
Transport	*12.3*	9	10
- *Households*	*8.4*	15	22
- *Transport sectors*	*3.9*	-4	-17
Residential	*11.3*	-17	-28
ETS Sectors	*5.4*	-16	-22
Other sectors	*15.5*	-5	-18
- *Air transport*	*4.3*	-6	-17
- *Other*	*11.2*	-5	-18
Domestic CO_2	*44.6*	-6	-13
Domestic CO_2 (wo Air transport)	*40.2*	-6	-13
- *Combustible fuels*	*22.5*	*-11*	*-23*
Other GHG	*8.2*	-9	-11
- CH_4	*4.3*	-24	-27
- N_20	*3.6*	-24	-25
- *Fluorinated gases*	*0.2*	476	489
Domestic GHG emissions	*52.8*	-6	-13

[a] in $MtCO_2eq$

The baseline reduction of GHG emissions in Switzerland is explained by four major factors: (1) moderate GDP growth, (2) increasing energy efficiency, (3) the continuation of existing climate policies and (4) oil prices reaching 66 USD_{2008}/bbl in 2030. The next section presents the policy scenarios which are envisaged to further reduce Swiss GHG emissions.

3.4 Policy scenarios

3.4.1 Swiss scenarios

Two scenarios are under consideration, a first one where international agreements target rather limited abatement, and a second one where stronger abatement is agreed upon by all world nations. Since no specific threshold allowing to differentiate the two cases has yet been defined , using expert judgment and the scenarios of the Energy Modeling Forum 22 (Clarke et al., 2009), we define two sets of international abatement targets (see section 3.4.2).

The envisaged Swiss post-Kyoto policies, described in detail in table 3.5, are not aimed at achieving a first best optimum but rather take into account the specificities and interests of the various stakeholders that will be affected by the policies. Indeed, the policies divide the economy in four parts, which will face different carbon prices.

Table 3.5: Swiss emissions targets

	Scenario 1		Scenario 2	
	2020	2030	2020	2030
ETS[a]	-1.75 % p.a.		-2.9 % p.a.	
ETS CER purchase cap (% of abatement)[b]	40		50	
Transport (% of 1990 CO_2 emissions)[c]	-25	-42	-40	-60
Technical regulations on cars[d]	target on average emissions of new cars			
Combustible fuels (% of 1990 CO_2 emissions)[c]	-25	-33	-35	-50
Building improvement program (2010–2020)[e]	200 Mio. CHF p.a.[f]			
Total CER purchase cap (% of abatement)[c]	9	14	14	21

[a] Starts in 2013 on the basis of the average emissions in the period 2008–2012
[b] The cap on the purchase of certificates in the ETS sectors increase linearly over the periods 2010–2020 and remains unchanged from 2020–2030
[c] The values of the objectives increase linearly over the periods 2010–2020 and 2020–2030
[d] Modeled as a ban on the less efficient diesel and gasoline personal cars (5.4 l/100km and 6.1 l/100km) as of 2015
[e] Modeled as a discount on refurbishment costs (energy saving technologies)
[f] 130 Mio. USD_{2008}

Taxes, levies and CO_2 markets

The energy intensive sectors (ETS sectors) will participate as of 2013 in an ETS similar to the European Union (EU) ETS (Böhringer et al., 2009; Tol, 2009) and will be entitled to purchase a part of the required abatement through the purchase of certified emissions reductions (CER) purchased abroad. Our model simplifies the original policy requirement in four ways. Firstly, the future policies envisage that only large companies will participate in the emission trading whereas we assume that the totality of the sector takes part in the trading. Secondly, the companies taking part in the ETS might have the possibility not only to purchase CERs on the international market but also European Union Allowances (EUA) on the EU-ETS in case the ETS and EU-ETS are linked. We model a single international carbon market and therefore make no distinction between CER and EUA. Thirdly, similarly to the EU-ETS (Demailly and Quirion, 2006; Hepburn et al., 2006), it is envisaged that 80% of the allowances are distributed at first according to grand-fathering and only progressively the auctioned share grows to 70% in 2020 . We assume that 100% of the allowances are auctioned as of 2013. Fourthly, we only consider emissions related to the use of fossil fuels, i.e. CO_2 emissions from cement production, other than those resulting from the use of fossil fuels to produce heat, are not counted.

The transport sectors are potentially affected by two instruments. Firstly, as of 2010, the importers of transportation fuels will be required to offset a part of the transport emissions through the purchase of CERs. Assuming that the additional costs due to the purchase of the certificates will be passed on to the consumers through an increase in the price of transport fuels, we have modeled this through the implementation of a levy (tax), whose revenues are sufficient to purchase the required amount of foreign certificates. Secondly, in order to ensure a minimum domestic abatement the sum of the purchases from the ETS and transport sectors is limited. Therefore, if the cap on the purchase of CERs is reached and taking into account that the ETS sectors have the priority in the purchase mechanism, a CO_2 tax will be introduced on transportation fuels to ensure achieving the abatement target of the transportation sectors.

As for the current CO_2-Law, combustible fuels will continue to be subject to a tax. Nevertheless an exemption will be introduced for those sectors taking part in the ETS. Finally, air transport is not subject to any constraint.

In order to evaluate the relative efficiency of the envisaged scenarios, we have also simulated the implementation of a uniform CO_2 tax, applied to the whole economy except from air transport, aimed at achieving equal domestic and total reductions.

In addition to the various economic instruments, two specific programs will also contribute to the overall Swiss abatement effort: an average emission target for the CO_2 emissions of new passenger cars and a building improvement program.

Car regulations

Both policies under consideration envisage an average emission target value for the CO_2 emissions of new passenger cars, with the same requirements as those that will be imposed in the EU (European Commission, 2009b). The average emissions of new cars will be limited to 130 gCO_2/km as of 2012 and to 95 gCO_2/km in 2020.

Despite the technological richness of the MARKAL-CHTRA model, the number of available and future personal car types is rather limited to model precisely this aspect of the policy. Instead, as of 2015, we have implemented a technical restriction on the purchase of the less efficient diesel and gasoline personal cars (5.4 l/100km and 6.1 l/100km). This leaves the following choices to the consumers: gas internal combustion engines (ICE) cars (8.2 l/100km), efficient diesel and gasoline ICE cars (5.1, 5.8 l/100km), as well as hybrid cars using gas, diesel and gasoline (6.2, 4.2, 4.9 l/100km). As MARKAL models are perfect foresight models, due to anticipations, the restrictions have an effect before their implementation and, already in 2013, approximatively one half million tons of CO_2 are avoided. The abatement achieved by this measure exceeds 1.1 $MtCO_2$ in 2020, which represents respectively 26% and 18% of the required transport sector abatement efforts in scenarios 1 and 2.

Building improvement program

In the period 2010–2020, the revenue of the tax on combustible fuels will be affected up to one third of its values or maximum 200 Mio. CHF[4] to a building improvement program, and the rest will be redistributed to households and

[4] 130 Mio. USD_{2008}

economic sectors through social security[5]. The building improvement program consists of financial help from the government to undertake refurbishments of houses and buildings with the scope of improving their energy efficiency.

The use of a hybrid model with a bottom-up residential sector allows modeling endogenously this building improvement program. We have implemented a procedure which determines a reduction in the investment prices of energy saving technologies (e.g. insulation) as well as efficient technologies such as heat pumps or solar. This affects relative prices in MARKAL-CHRES and ensures that households increase their investments in these technologies. The price rebate is calculated so that the difference between the real costs of the investments and the actual costs borne by the households after the rebate is equal to the 200 Mio. CHF available for the program. In GEMINI-E3, we have considered that the government spends this amount in constructions (services sector).

When analyzed independently from all other instruments, we find that the building improvement program would save annually up to 680'000 tCO_2 by 2020, representing 23% and 15% of the abatement required in the residential sector in scenarios 1 and 2 respectively, at a shadow price of 191 USD_{2008}/tCO_2eq.

3.4.2 International scenarios

Climate policies will only be efficient in the long run if major agreements are found to limit emissions globally. There is no doubt that the historical responsibility of climate change lies with developed countries (Höhne and Blok, 2005) and that it would be unfair to jeopardize the development process of the rest of the world. Nevertheless, it remains true that, without appropriate coordinated action of emerging nations, any efforts by the developed countries would be vain.

With that in mind, the level of emissions abatement to be included in the future Swiss policies will depend on involvement of the rest of the world in resolving the climate change problem. In this paper we consider two cases, where two different international agreements are agreed upon and enforced. The proposed target for the "low" and "high" scenarios for 2020 and 2030 are presented in table 3.6. The "low" scenario is used to analyze the first Swiss scenario, where

[5]In view of the fact that our model has a single representative household that owns the capital, and assuming that companies would return the money to the capital owner, we have modeled the redistribution of the tax as a simple lump-sum transfer.

a weak international agreement is reached, whereas the "high" scenario is used for the second Swiss scenario, where all countries more actively participate in the global effort. The high scenario is based on International Energy Agency (2009) where DCS get binding targets as of 2020. World emissions in 2030 would be approximately at the level of 2001. Figures 3.3 and 3.4 show the international abatement targets for both scenarios.

Table 3.6: International emissions targets (% of 2001 emissions)

Target year	2020		2030	
Scenario	Low	High	Low	High
CHE	-22	-32	-30	-46
EUR	-20	-30	-30	-45
OEC	-20	-30	-30	-47
JAP	-20	-30	-30	-47
OEU	-[a]	-10	-10	-23
DCS	-[a]	-[a]	0[b]	-13[b]

[a] baseline emissions
[b] % of 2020 emissions

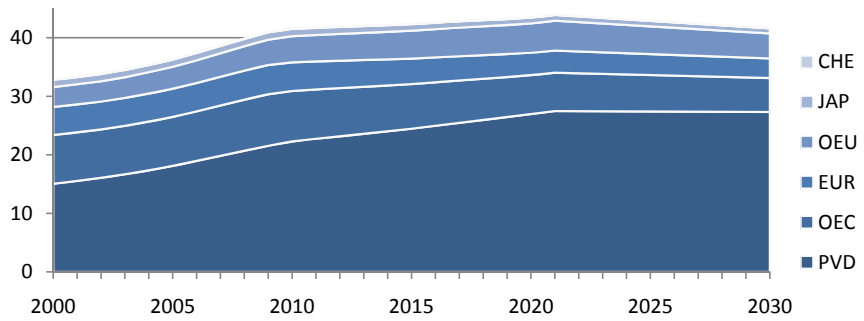

Figure 3.3: Scenario 1 GHG emissions targets ($GtCO_2eq$)

For the sake of simplicity, we assume that all regions, except Switzerland, fully participate in a global emissions cap and trade system, thus equalizing marginal abatement costs across all regions and providing a single world price for carbon[6]. When no binding target is defined for a region, we cap its emissions to the baseline emissions in order to avoid that the overall effect of the policies is jeopardized by carbon leakage.

[6]For simulations taking into account delayed participation or fragmented climate regimes see van Vuuren et al. (2009) and Hof et al. (2009).

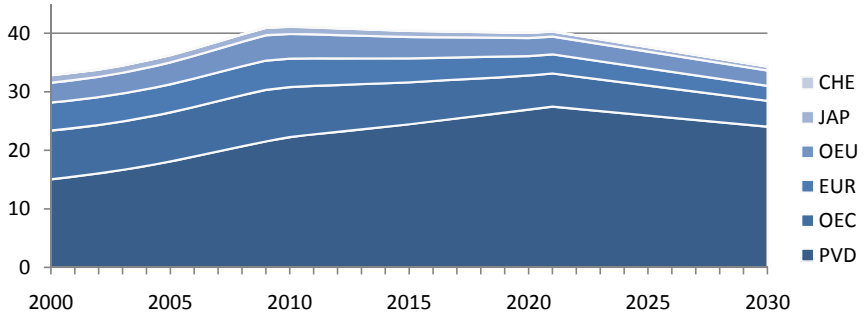

Figure 3.4: Scenario 2 GHG emissions targets ($GtCO_2eq$)

3.5 Results

3.5.1 Scenario 1

Carbon prices and emissions reductions

Tables 3.7 and 3.8 present respectively the taxes that allow achieving the objectives and the detailed emissions abatements in the various parts of the Swiss economy. As expected, the levy collected on transport fuels to offset the emissions of the transport sector is small in view of the low price of foreign CO_2 certificates. The additional combustible fuel tax is significant as it would have to reach approximately 89 USD_{2008}/tCO_2eq by 2020 to obtain 25% abatement, despite the technical possibilities offered by MARKAL-CHRES and the building improvement program. The price of the allowances in the ETS market remains rather low in view of the fact that the baseline abatement in those sectors is quite pronounced already, leaving small additional abatement to meet the target. As a consequence, the ETS carbon price equals the international price of CERs.

The uniform tax presented in the last line of table 3.7 allows an equivalent total CO_2 abatement as the combination of the tax, levy and ETS markets. It is determined with a cap on the purchase of CERs set at the level of one reached with the combination of the instruments and maintaining both the building improvement program and the technical regulations on cars.

The figures relative to abatement of the emissions due to combustible fuels and those from the residential sector in table 3.8 suggest that modeling the use of combustible fuels in commercial buildings with an energy-systems model, as it is

Table 3.7: Swiss environmental taxes and prices of certificates/allowances in scenario 1 (USD_{2008}/tCO_2eq)

	2013	2015	2020	2030
Transport fuels levy	0.04	0.1	1	3
Combustible fuels tax	30	42	89	24
ETS certificate price	1	1	2	8
World certificate price	1	1	2	8
Uniform tax	*7*	*7*	*7*	*8*

the case in the residential sector, would lower the estimation of the combustible fuels tax. Indeed, it seems reasonable to assume that technologies available for residential buildings can to a large extent also be used for commercial buildings and that the tax should trigger a similar magnitude of abatement. Even if a part of the difference can be explained by the implementation of the building improvement program which triggers an abatement in the residential sector of 0.6 $MtCO_2$ and the fact that some industrial processes are still part of the other sectors, the effect of the tax on the other sectors (-20%) seems rather limited when compared to the reductions in the residential sector (-34%).

Both the transport and the ETS sectors can purchase CERs within predefined limits. Table 3.9 shows that in the first scenario the ETS sectors purchase a very limited amount of CERs to reach their target. In the transport sectors the small amount levied on fuel imports allows the purchase of sufficient certificates to meet the 25% abatement target, but it is mainly the introduction of the regulations on cars that triggers the domestic abatement that can be observed when comparing tables 3.4 and 3.8. The purchase cap on CERs is not reached, indicating that the policies ensure sufficient domestic abatement without having to impose an additional tax on transport fuels.

Economic and welfare impacts

Table 3.10 presents the impacts of scenario 1 on welfare (households' surplus) as well as its decomposition into the gains and losses of the terms of trade (GTT), the trade of emissions permits and the deadweight loss of taxation (DWL)[7]. Fur-

[7]See annex C.3 for more detail on the calculation of the welfare components.

Table 3.8: Variation of the Swiss GHG emissions in scenarios 1 and 2 (% of 1990)

		Scenario 1		Scenario 2	
	1990[a]	2020	2030	2020	2030
Transport	*12.3*	2	-3	2	-3
incl. CER		-25	-42	-40	-60
- Households	*8.4*	5	5	5	6
- Transport sectors	*3.9*	-5	-19	-6	-21
Residential	*11.3*	-39	-47	-53	-75
ETS Sectors	*5.4*	-18	-26	-20	-32
incl. CER		-23	-35	-30	-48
Other sectors	*15.5*	-10	-19	-15	-23
- Air transport	*4.3*	-5	-17	-5	-16
- Other	*11.2*	-13	-20	-19	-26
Domestic CO_2	*44.6*	-15	-23	-21	-32
Domestic CO_2 (wo Air transport)	*40.2*	-16	-23	-22	-33
- Combustible fuels	*22.5*	-26	-34	-36	-51
Other GHG	*8.2*	-10	-10	-11	-11
- CH_4	*4.3*	-25	-26	-27	-26
- N_20	*3.6*	-25	-25	-26	-26
- Fluorinated Gases	*0.2*	477	490	477	491
Domestic GHG emissions	*52.8*	-14	-21	-19	-28
Net GHG emissions	*52.8*	-21	-31	-30	-43

[a] in $MtCO_2eq$

thermore, it presents the impacts of the uniform CO_2 tax that would allow an equivalent total and domestic CO_2 reductions. The welfare components are presented as a percentage of total households' consumption (HC). In the first scenario, the impact of the climate policies on welfare is above a third of a percentage point. The DWL is the main element influencing the welfare as both the GTT and the capital transfers due to the purchases of permits remain limited.

The numbers in the table 3.10 also show that if a uniform CO_2 tax is used instead of the combination of instruments, the resulting welfare effects are slightly smaller. The difference between the two welfare effects can be interpreted as a loss of efficiency caused by the differentiation of the carbon price among sectors.

As expected, the overall impact of climate policies is negative for both production and consumption. Nevertheless, some sectors are more affected than others

Table 3.9: Swiss purchase of certificates in scenarios 1 and 2 ($MtCO_2eq$)

	Scenario 1		Scenario 2	
	2020	2030	2020	2030
Transport	3.3	4.8	5.1	7.0
ETS	0.3	0.5	0.5	0.9
Total	3.5	5.3	5.6	7.8
Purchase cap	4.8	7.6	7.4	11.3
%1990 GHG emissions	9%	14%	14%	21%

Table 3.10: Economic impacts of scenarios 1 and 2 in Switzerland (% of HC)

	Scenario 1		Scenario 2	
	2020	2030	2020	2030
Households' Surplus	-0.33	-0.34	-0.49	-0.47
GTT	0.06	-0.03	0.14	0.09
Sales of permits	0.00	-0.01	-0.01	-0.08
Deadweight Loss	-0.39	-0.29	-0.62	-0.47
in case of uniform tax				
Households' Surplus	*-0.26*	*-0.34*	*-0.39*	*-0.43*
GTT	*-0.04*	*-0.08*	*0.09*	*0.06*
Sales of permits	*0.00*	*-0.02*	*-0.01*	*-0.08*
Deadweight Loss	*-0.21*	*-0.24*	*-0.47*	*-0.41*

and some even benefit from the policies. The most affected sector is the refined petroleum sector, whose demand from households drops by 29% in 2030. Such structural changes are obviously the aim of climate policies. The production of refined petroleum products as well as the imports are also quite strongly affected as they both decreases by approximately 10% compared to the baseline. In this scenario, the gas sector turns out to be the economically viable alternative to petroleum products. The households' consumption of gas increase (66%) is obviously supported by a strong increase of imports (39%). The electricity sector also strongly benefits from the policies and sees its production increase by almost 4% in 2030. In view of the small transport fuels levy, as expected, most transport sectors are only slightly negatively affected. The rail and road passenger transport sectors do nevertheless slightly benefit from a slight reduction in personal

car usage. Furthermore, pipeline transport production increases by up to 5.8% as it benefits from the increase in gas consumption.

Each scenario having a specific international framework, it is interesting to say a word about international results despite the fact that they are not directly comparable with those of Switzerland. The first scenario assumes that OEU and DCS are not subject to emissions caps (other than their baseline emission) before 2020. As a consequence, both of these regions are in a position to sell CERs and have therefore positive welfare effect. The effects in other regions are smaller than in Switzerland, as the price of carbon is equal across sectors, no minimal share of domestic abatement is imposed and all GHGs are included in policies. In view of the small price of world certificates, the Swiss welfare losses are mainly due to the combustible fuels tax which is a purely national measure and is therefore not connected to the international emissions certificates market (see figure 3.8).

The residential and transport sectors

The coupled MARKAL-CHRES and MARKAL-CHTRA models allow us to analyze the technical implications of the scenarios more in detail.

Figure 3.5 shows that in the residential sector the combination of the combustible fuel tax and the building improvement program reduce both the heating oil and gas usage by respectively 14% and 66% compared to the baseline in 2030. Except in existing multi-family houses where the use of heating oil remains predominant, electric heat pumps become the predominant technology for space heating, which triggers the major part of the increase of electricity use (21% compare to the baseline). The instruments also trigger an increase of 9% in the use of insulation and other energy saving technologies.

Figure 3.6 presents the personal cars usage by car types in Billion vehicle kilometers per year(bvkm/a) and shows that the car regulations have a significant impact on the composition of the of vehicles fleet. The increase of gas powered vehicle is responsible for the increase of gas consumption by households as it largely compensates the decrease observed in the residential sector. The regulations also trigger an increased penetration of all types of hybrid cars, which is limited to hybrid diesel cars in the baseline.

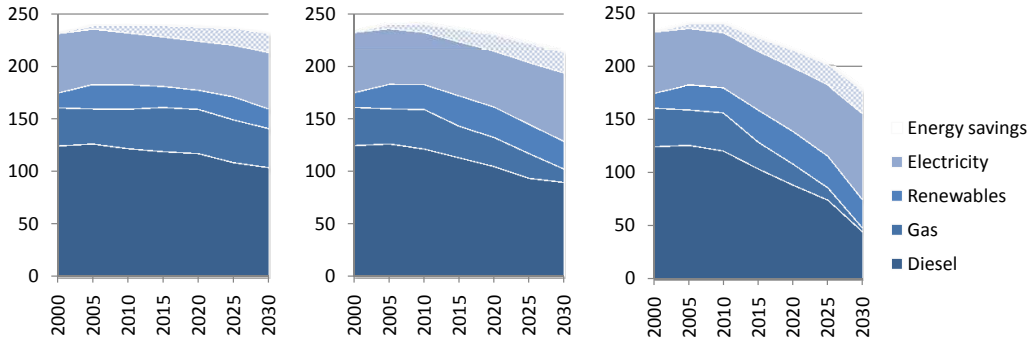

Figure 3.5: Baseline / Scenario 1 / Scenario 2 fuel mixes in the residential sector (PJ)

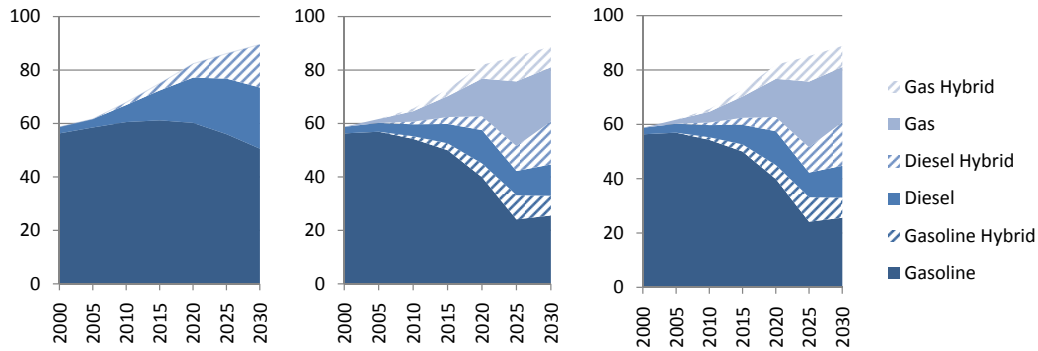

Figure 3.6: Baseline / Scenario 1 / Scenario 2 use of personal cars by types (bvkm/a)

3.5.2 Scenario 2

The second scenario targets a total reduction of GHG emissions by 30% in 2020 and 44% in 2030 using the instruments presented in table 3.5.

Carbon prices and emissions reductions

Tables 3.11 and 3.8 present respectively the taxes that allow achieving the objectives of scenario 2 and the detailed emissions abatements in the various parts of the Swiss economy. The levy collected on transport fuels, despite being up to five time higher than in the first scenario, remains at very reasonable levels as the price of foreign emission certificates remains low. Such a levy would trigger an increase in the price of gasoline of approximately 1.2 cents per liter. The combustible fuels tax is expected to increase strongly if an abatement of 35% by 2020 is desired. Indeed, achieving such a strong domestic abatement over a single

decade would require significant incentives and despite the building improvement program a tax reaching 190 USD_{2008}/tCO_2 would be necessary. As in the first scenario, the price of allowances in the ETS market remains rather low, in view of the moderate abatement compared to the baseline and because of the possibility to undertake 50% of this abatement abroad through the purchase of cheap emission certificates, in particular before 2020. By 2030 the certificates would reach 30 USD_{2008}/tCO_2. Figures 3.7 presents the domestic emissions for the various sectors and confirms that the share of emissions caused by motor fuels increases significantly from 23% in 1990 to 29% in 2030. Combustible fuels, ETS sectors excluded, see their share shrink from 43% to 36%.

Table 3.11: Swiss environmental taxes and prices of certificates/allowances in scenario 2 (USD_{2008}/tCO_2eq)

	2013	2015	2020	2030
Transport fuels levy	0.2	1	2	18
Combustible fuels tax	49	74	190	134
ETS certificate price	2	3	6	30
World certificate price	2	3	6	30
Uniform tax	*31*	*47*	*103*	*82*

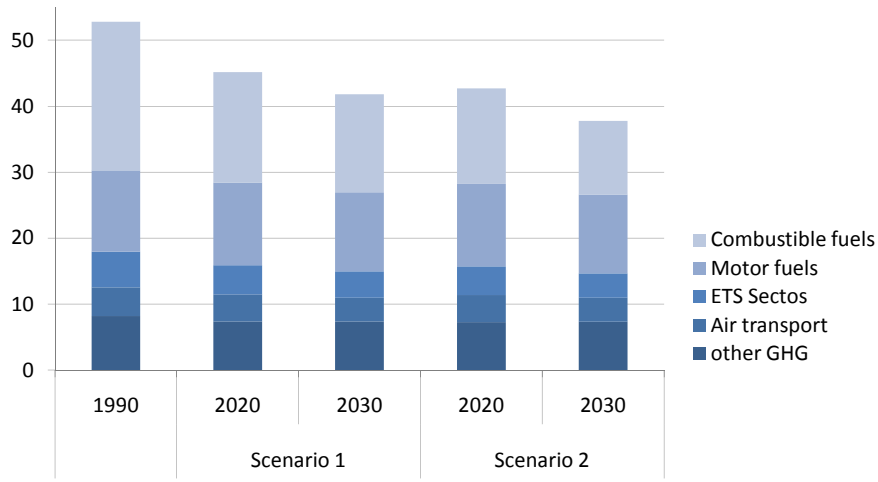

Figure 3.7: Domestic Swiss GHG emissions, including international aviation ($MtCO_2eq$)

The tax on combustible fuels seems particularly high when compared to the uniform tax that would allow an equal domestic and total reduction of emissions

and might trigger questions on the social equity aspects of the envisaged policies. Figure 3.8 shows clearly that the transport sector contributes greatly to achieving the overall objective in both scenarios, but to a very large extent through the purchase of CERs. The tax on combustibles fuels achieves 65% of the domestic abatement in 2030 and when adding the contribution of the building improvement program this share rises to 75%. When considering the total emissions reductions, 77% is achieve by the combustible fuels tax and the purchases of CER by the transport sector.

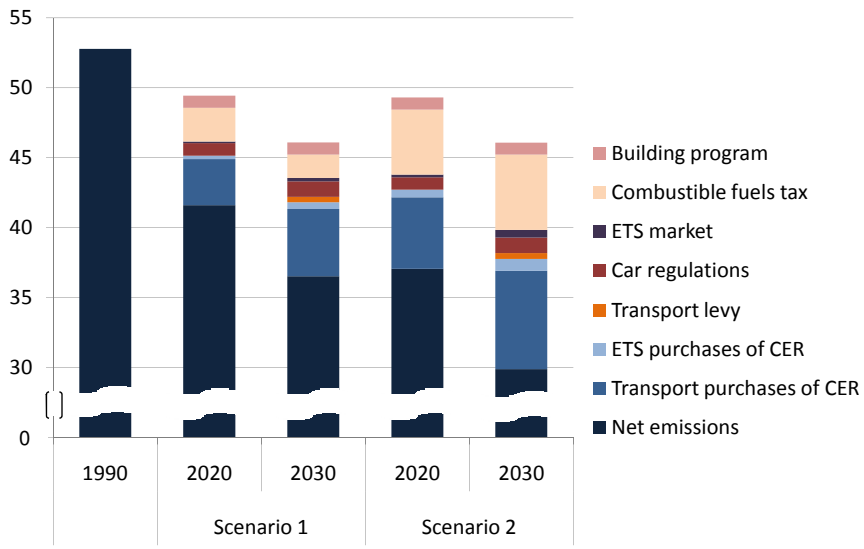

Figure 3.8: Net Swiss GHG emissions, CER purchases and abatements by responsible instrument ($MtCO_2eq$)

Regarding the purchase of emission certificates by the transport and the ETS sectors, table 3.9 shows that, similarly to the first scenario, the overall emission cap is not reached and as a consequence no additional tax on transport fuels is required. The purchase of foreign emission certificates by the transport fuel importers financed by the levy reaches 7.8 tCO_2eq in 2030, which represents approximately 15% of 1990 emissions. As in the previous scenario the domestic abatement in the transport sector is attributable to the regulations on passenger cars rather than to the small increase of transportation fuels' prices.

Economic and welfare impacts

Table 3.10 presents the impacts of scenario 2 on welfare. As expected, the impact on welfare is more substantial than in the first scenario. The DWL reaches 0.6% of households' consumption in 2020 and the gains of the terms of trade are not sufficient to offset this. Again, the comparison with the uniform tax case confirms that setting up instruments which lead to differentiated marginal costs of abatement is suboptimal in terms of welfare. In view of the low prices of foreign emission certificates, the influence of their purchase on welfare remains low.

As expected, the overall impact of climate policies on both production and consumption is negative and stronger than in the previous scenario. The strongest effect is on the petroleum products sector, which is significantly affected (-18% of production in 2030), mainly because of a strong decrease in final consumption (-46%). When comparing with the previous scenario, with higher taxes gas turns out to be less of a viable substitute to petroleum products and therefore the substitution toward electricity is stronger. Gas consumption nevertheless increases by more than 50% and electricity consumption jumps by almost 40%. The electricity sector is the major beneficiary in this scenario as it increases its production by 6.7% in 2030. Again, the air transport sector is very slightly affected as it does not face any carbon price.

From the international perspective, the second scenario assumes stronger abatements and international agreements that would involve in the long run all regions with specific emissions reductions. By 2020, nevertheless, it is expected that DCS would only be restricted to their baseline emissions and, as a consequence, it is the only region selling large amounts of CER and therefore enjoying welfare gains. Switzerland is more affected than other regions before 2020, with the exception of OEU which is extremely sensitive to climate policies in view of its energy and energy intensive goods exports. In 2030, EUR and OEC face stronger welfare effects, due in particular to the greater baseline GDP growth that is expected in those regions.

The residential and transport sectors

Figure 3.5 shows that the high tax on combustible fuels combined to the building improvement program reduces the use of gas and diesel in the residential sector

by respectively 90% and 57% in 2030 compared to the baseline. The use of electric heat pumps, which have an energy efficiency three to four time superior to conventional diesel boilers, allows compensating a large share of the final energy demand and increases the use of electricity by 50%. The rest of the final energy is compensated by an increase of 44% in the use of renewables and an additional installation of energy saving technologies (19%).

Figure 3.6 show that only the car regulation influence the personal cars fleet composition. Indeed, the limited amount of the levy remains without effect for the personal cars. The use of the uniform tax does not further affect the personal cars fleet and has no impact of other parts of the transport sector, which are very inelastic over the time horizon until 2030.

3.6 Conclusions

The use of hybrid and coupled models in the framework of the economic assessment of climate policies is increasingly popular and this study underlines the benefits of this methodology. It also presents an innovative soft-coupling procedure between a world CGE model (GEMINI-E3) and two energy-systems models (MARKAL-CHRES and MARKAL-CHTRA) modeling specifically the Swiss residential and transport sectors. Linking the models allows modeling the numerous aspects of the future climate policies, which can be of both technical and economic nature.

Our coupled model simulates all the different policy instruments that are envisaged in Switzerland for the post-Kyoto period endogenously and therefore allows analyzing both envisaged scenarios in different international frameworks. In the first scenario, we simulate moderate abatement targets with weak and incomplete international agreement, whereas the second scenario aims at more stringent abatement in the case where stronger international abatement objectives would be agreed upon.

Our simulations show that both policies have moderate economic impacts on the Swiss economy. In the first scenario, the various instruments would trigger a loss of welfare of about a third of a percent in 2020. In the second scenario, the maximum welfare loss would reach half percent in the same period. With a model that would consider induced technical progress and first-mover advantages, those

economic impacts should be even lower. Furthermore, the welfare costs do not account for the avoided damages due to climate change, the potential adaptation costs or the ancillary benefits such as the avoided local local air pollution. Nevertheless, we also show that welfare costs of mitigation could be further reduced by the introduction of a uniform tax.

Two major factors affect the efficiency of climate policies. On the one hand, within a given country, the necessity to differentiate the carbon prices faced by different sectors is generally defended by arguments related to international competitiveness and carbon leakage. Grubb et al. (2005) pinpointed that concerns about competitiveness led to excessive generosity for some sectors in the first phase of the EU-ETS allocation. In our framework, we show that while ensuring the global emissions abatement levels, thus avoiding leakage, the competitiveness argument does not hold in Switzerland. Indeed, Swiss welfare suffers from the advantage given to transport and ETS industries by the introduction of the diversified instruments and overgenerous caps on CERs purchases. On the other hand, national restrictions on the purchase of CERs are a major factor affecting the efficiency of climate policies but they are necessary from the perspective of international equity. In the Swiss case, all sectors facing the combustible tax are deprived from using any sort of flexibility mechanism, thus increasing the cost of emissions abatement.

Both scenarios trigger an important switch away from petroleum products. In the first scenario, this turns out to be very beneficial for the gas sector that profits from the increase of gas ICE and hybrid personal car. In the second scenario, a doubling of the tax on combustible fuels pushes further toward the use of electricity in the residential sector. Both policies generate gains from the terms of trade but they do not offset the deadweight loss of taxation.

Interestingly, in both scenarios the caps on the purchase of foreign emission certificates are not reached. The implications are twofold. On the one hand, the envisaged tax on transport fuels is not necessary to ensure the minimum domestic abatement and, on the other hand, additional purchases of certificates, particularly in the residential sector, would be possible without jeopardizing the domestic emissions targets.

From the technology perspective, we show that the transport sector is very inelastic to prices and that the car regulations are the only instrument affecting the

personal cars fleet composition. The car regulations are responsible for a strong penetration of hybrid cars and gas cars in general. This might be significantly different if additional vehicles types, in particular personal cars such as plug-in hybrids and electric, would be included in MARKAL-CHTRA. As expected, the high taxes in the residential sector trigger a switch away from diesel and gas in favor of renewables and electricity, mainly thanks to the installation of efficient heat pumps.

In conclusion, both scenarios seem realistic and do not have dramatic impacts on the Swiss economy. This is due partly to the fact that in both scenarios the price of foreign emission certificates remains relatively low, allowing cheap offsetting of Swiss emissions in transport and ETS industries. Nevertheless, the comparison with the uniform tax confirms that Swiss society as a whole would be better off without the differentiation of the economic instruments between different sectors that is aimed at increasing the acceptability of climate policies.

Acknowledgements

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Conclusion

This thesis discusses questions relative to the implementation of Swiss post-Kyoto Swiss policies and provides novel methodologies to assess their implementation. This final conclusion address both aspects separately, by summarizing the key improvement brought to the coupling method and highlighting the major implications for policy makers. Finally, it underlines some limitations and provide ideas for future research.

Coupling

As a conclusion to a workshop held in Paris on April 20–21, 2005, which brought together several research teams that explore hybrid modeling, Hourcade et al. (2006) identified the following possible approaches to be explored in the future as well as different modeling strategies dependent on the objective of the model.

- *A TD [8] model that partly renounces the conventional macro-economist's toolkit (constant elasticities of substitution (CES), and the autonomous energy efficiency index (AEEI)), and relies on innovative ways to represent not only energy supply but also energy end-use technologies as described by BU [9] analysis, and technology adoption as described by microeconomic studies, especially regarding households.*
- *A TD model that increases its disaggregation level and resorts to Leontief fixed-input ratios to include a reduced-form BU module of some part of the energy system (e.g. in energy supply or the transport sector).*

[8] Top-down
[9] Bottom-up

- *A BU model that includes: empirically estimated micro-economic parameters related to technology choice; functions to clear markets for energy, other intermediate inputs, and final goods and services based on changes in the cost of production, using either price elasticities or more advanced CGE techniques that utilize consumer utility and firm profit functions; and functions to balance government budgets, exchange rates, and capital and labor markets.*

- *A composite hybrid model that includes all of the major theoretical and structural characteristics of the most advanced TD models along with the major characteristics of the most advanced BU models, with technological detail in all sectors and behavioral parameters that are empirically estimated from microeconomic and macro-economic research. While such a model would present the greatest challenge in terms of theoretical consistency, mathematical complexity and empirical estimation, it nonetheless represents an objective that some modelers might aspire to, and has been colloquially referred to as the "Holy Grail".*

In this thesis, I have explored the first two approaches through specific amendments of the GEMINI-E3 model that have allowed the coupling with MARKAL sub-models to assess the economic impacts and the efficiency of Swiss post-2012 climate policies. From a modeling perspective the three hybrid models developed in this thesis represent three steps toward a more precise and realistic modeling of climate policies using the soft-coupling approach and complement the scientific literature on the subject.

First hybrid model

In the first chapter, with a rather simple dichotomic coupling procedure that improves earlier work by Drouet et al. (2005b) by providing a uniform accounting method for GHG emissions, we show that marginal abatement curves in the residential sector change quite substantially when the top-down model is coupled with the bottom-up model. Indeed, the technological options in the bottom-up model provide for lower abatement costs for high abatements.

In view of the single emission objective in the target year and the regular structure of the tax vector (constant or linearly growing), the coupling procedure

consists of alternative runs of both models, while ensuring that the fuel mix calculated in the MARKAL model is adequately accounted in GEMINI-E3. The coupling module uses the tax to ensure that the emissions calculated by GEMINI-E3 converge to the target defined in the policy.

Second hybrid model

In the second chapter, the hybrid model is further developed to harmonize investments in the residential sector and energy prices between the sub-models as well as enable a world carbon market that allows to simulate policies combining domestic abatements and the purchase of foreign emissions certificates.

Despite the additional number of coupling variables, the fundamental concept behind the coupling method is similar the one used in the first chapter. Two differences are nevertheless worth mentioning. First, the use of the fuel mix and investment information are not only used to amend the share parameters as in the first chapter, but also to dynamically calibrate the technical progress parameter, thus ensuring the adequate feedback on prices. Second, the coupling algorithms allow to consider simultaneously domestic and total targets. The two stage "iterative" nature of the algorithms also ensures a convergence of the variations of energy prices, which are not only influenced by international policies but also by ambitious national abatement objectives.

Third hybrid model

In the third chapter, the hybrid model is further tailored to the policies devised by the FOEN as a follow-up of the consultation procedure on the revisions of the CO_2 Law. The most notable amendments to the the model are certainly the disaggregation of the transport sectors in GEMINI-E3 and the coupling with the MARKAL-CHTRA model. The disaggregation of the transport sector allows GEMINI-E3 to assess the potential modal switch that can be triggered by climate policies, whereas MARKAL-CHTRA provides for the technological details for each mode of transport . Nevertheless, from a coupling perspective, the major difference with previous models is the absence of control variable in the coupling module. Indeed, in this model, GEMINI-E3 is directly provided with the emission reduction paths for the various parts of the economy and calculates all tax vectors

endogenously. Consequently, in order to ensure the convergence of the coupling, the taxes calculated by GEMINI-E3 are not passed directly to the MARKAL sub-models. The algorithm 4 in appendix C.4 shows precisely the "smoothing" method used to ensure the convergence of the coupling procedure.

Post-2012 climate policies

As presented above, he three models devised for this thesis are increasing in complexity in order to answer increasingly sophisticated questions relative to the future of Swiss climate policy. Each model build on the previous one and provide additional modeling details, thus providing increasing relevance for policy makers.

This sections presents the key results of the thesis from a climate policy perspective and provide a summary of the answers to the research questions.

The residential sector

In the first chapter I show that heat pumps and energy saving technologies like insulation have a great potential to reduce the carbon footprint of the residential sector. Furthermore, keeping in mind the perfect information and perfect foresight nature of the MARKAL-CHRES model, I show that the simultaneous use of taxes and technical regulations does not seem to provide cumulative benefits. Nevertheless, taking into account that the model does not capture a number of market imperfections (e.g. information costs, owner-renter issue, ...), technical regulations could actually help ensuring that the residential abatement potential is achieved. Finally, growing taxes targeting all GHG prove to be most effective.

The following chapters of the thesis also confirmed with more complex coupled model that the residential sector offers the cheapest abatement opportunities in Switzerland. Nevertheless, the policies assessed in the first paper to specifically evaluate the potential of the residential sector do not take at all into account that a part of the total abatement could be undertaken through the purchase of international emissions reductions certificates. With that in mind, I have devoted the second part of my thesis to analyze different policy scenario focusing on that aspect, including the popular idea of climate neutrality.

Climate neutrality

The results in the second chapter show that, at the prices of international emissions reduction certificates around 35 USD_{2001}, Switzerland could offset all of its remaining domestic emissions (climate neutrality) and even emissions embodied in its imports at a net welfare cost which would not excede 0.14% of its final household consumption over the whole period 2008-2050. In a more stringent international environment where international certificates would cost approximately ten times more, it could nevertheless follow a path toward sustainability, as promoted in contraction and convergence scenarios (Meyer, 2004), and reach a target of 2 tCO_2eq per capita by 2050 without affecting welfare much further. When considering the gains in the terms of trade the welfare impacts are even positive. Finally, the addition of a -50% domestic emissions target further increases the gains from the terms of trade and has ultimately a positive effects on welfare, provided that the revenue of the tax not used to purchase international certificates is redistributed to the population.

In the second chapter, all policies consider that domestic abatements would be achieved by means of a GHG tax applied through all sector of the economy. From a modeling perspective this would also be equivalent to implementation of a domestic market of emissions certificates where all sectors could trade certificates among each other. Even though such solutions are promoted by economist as being most efficient to achieve emissions reductions targets, the reality of the political arena makes then difficult if not impossible to implement in view of the influence of some major economic actors. With that in mind, the third chapter was dedicated to the analysis of "real word" possibly acceptable policies as devised by the FOEN.

Acceptable policies

The third chapter presents a complete analysis of all the instruments envisaged for the revision of the Swiss CO_2 Law and compares it with the implementation of a uniform tax across sectors, thus requiring a more complex hybrid model capable of simulating endogenously all policy instruments. It shows that, in a framework where carbon leakage is controlled, policies that are devised to safeguard the competitiveness of energy intensive sectors, imply an excessive cost on welfare.

Furthermore, the envisaged policies over-allocate the rights to purchase emissions certificates of a small number of sectors (industries participating in the ETS market and transport), thus imposing the burden of domestic emissions reduction and high taxes on the rest of the economy. Nevertheless, in view of the results, the additional burden on the rest of the economy seems limited and the envisaged policies appear to focus on the sectors where the abatement costs are the lowest.

The welfare impacts due to the uniform tax are nevertheless significantly higher than those in chapter 2. Two main reasons explain this difference. On the one hand, the gains from the terms are smaller mainly because of differences in the international scenarios. On the other hand, taxes are higher because of a number of differences between the models. Firstly, in the third models, the MARKAL-CHRES model has been fixed to its baseline for the first decade to avoid that anticipations would start in years that have already passed, thus putting additional pressure in the later decades to undertake the abatement. Secondly, air transport is not taxed in the third model and, consequently, more pressure is put on other sectors to achieve similar total abatement. Thirdly, baseline calibrations are slightly different between the models. Finally, the transport disaggregated IOT is not comparable in all points to the IOT used in the first two chapters.

Therefore, considering that it is highly unlikely that Swiss climate policies will resemble those assessed in the second chapter and in view of the modeling improvements in the third chapter, the higher welfare impacts optained in the third chapter are more realistic than those of the second chapter for equivalent abatement targets.

Limitations and further research

This thesis provides a number of insights in the field of post-2012 climate policies. Nevertheless, the results should be considered in the light of the assumptions made and the limitations of the models. If coupling the Swiss residential and transport sectors has allowed to remove some of the uncertainties related to a number of parameters in GEMINI-E3 (e.g. elasticities and technical progress), the rest of the models remains a standard CGE model with all known limitations. For example, the assumptions made to calibrate the models are of utmost importance; e.g. future GDP growth and oil prices have a direct influence on the costs of climate

policies. In this respect, the calibration of some parameters could be further improved by additional econometric work and the use of a Monte Carlo methods would provide useful informations on the sensitivity of the models to different parameters.

It is also important to recall that all assessments of climate policies carried out in this thesis do neither take into account the future benefits of avoiding climate change nor potential adaptation costs to those changes. Indeed, such considerations do not seem relevant in the framework of the assessment of mitigation policies as the contribution of Switzerland to the global GHG emission is almost insignificant and, therefore, Switzerland cannot directly influence climate changes on its territory. Consequently, the assessment of Swiss mitigation policies focuses on the efficiency of the means to contribute to the global mitigation. In this thesis the efficiency is first measured in terms of GDP and, in the second and third chapters, in terms of aggregated welfare.

The hybrid models used in this thesis also present specific limitations in terms of methodology as well as in their representation of the electricity and the transport sectors. Furthermore, the acceptability of climate policies would deserve further attention.

Methodology

All along this thesis, various coupling algorithms and methodologies have been tested but only some could be successfully implemented. For example, the use of "oracle" based convex optimization methods such as the Proximal-ACCPM (see Babonneau et al., 2006), which have successfully been used to couple CGE and climate models (e.g. Drouet et al., 2006), is not appropriate for coupling GEMINI-E3 with the MARKAL sub-models due to non-convexity in the sub-models when controlled by the coupling module. Furthermore, in cases where the emissions abatement path is exogenously defined by the policy, i.e. like in the third chapter, the coupling procedure can fail to reach the exact path because the energy models can switch between solutions with only marginal variations of the input variables. Nevertheless, through an additional run of the GEMINI-E3 model I could ensure that both models were aligned with an emissions path only slightly different from the one defined in the policy. Finally, some coupling variables cannot be directly exchanged between the models. Indeed, in order to ensure the convergence, the

coupling algorithm only passes a fraction of the changes in the tax values at each iteration, thus increasing significantly the time required to reach a solution. This thesis presents effective procedures that have allowed the coupling of GEMINI-E3 and MARKAL models but it does not focus on the efficiency of the coupling procedures. In the framework of future research, the use alternative methods, such as heuristic algorithms, could certainly significantly reduce the time required to solve the hybrid models and would therefore be worth investigating, in particular if the complexity of the models would be increased.

This thesis shows the benefits of coupling top-down and bottom-up models in the framework of climate policy assessment. In particular it allows to circumvent the necessity to include imaginary backstop technologies in CGE models to limit the price of carbon and, therefore, provides a more realistic modeling framework. Nevertheless, this increases quite considerably the complexity of the models and mixes the different paradigms used in top-down and bottom-up models. GEMINI-E3, as a recursive dynamic CGE, is rather myopic when it comes to anticipating future costs. At the opposite, the MARKAL models have a perfect foresight and they minimize costs across the whole modeling time frame. With that in mind and in view of the fact that what is considered as an investment in the residential and transport MARKAL models is treated as intermediate and final consumptions in GEMINI-E3, I was able to harmonize both concepts without violating the fundamental principles of the CGE model. Nevertheless, the same could certainly not be applied to capital intensive sectors such as the electricity sector and alternative modeling frameworks, such as a hard coupling using the MCP approach, might be better suited. Attempting a coupling with a fully dynamic CGE model would also be an interesting way to explore.

From the international perspective, the results obtained in the second and third chapter show that beyond a certain threshold, the global MAC curve is rather steep, indicating that the model could not be used as such to study very stringent global abatement target. This is rather common with CGE models without backstop technologies (see Clarke et al., 2009). Some amendments could nevertheless help circumvent this drawback and would be worth taking on board in future research. A first technically challenging possibility, would be to link bottom-up models for all regions, at least for key emitting sectors. An alternative or additional option would be to include carbon capture and sequestration technologies, in particular for electricity generation from coal.

The electricity sector

The electricity sector in Switzerland is currently almost CO_2 free thanks to hydro and nuclear power. In all models used in this thesis, it is assumed that this would continue and that the electricity sector can be scaled up and down with a rather limited change in the fuel-capital mix. This further assumes that nuclear power plants phasing out would be replaced either by new nuclear power plants or by other "clean" capital intensive power plants such as wind or solar. In view of current political discussion, this might or might not be the case as it is also envisaged that gas combined-cycle turbines could also be used in the future to replace obsolete nuclear power plants. The results obtained in this thesis would certainly be affected if the later hypothesis would come true. Indeed, the electricity sector would face increased costs due to the taxation of the gas that would be used to produce a share of the electricity. Electricity would then be a less attractive substitute to fossil fuels, in particular in the residential sector. The use of electric heat pumps might therefore become more expensive and marginal abatement cost be pushed higher for the whole economy.

Including a more precise modeling of the electric sector to the coupled models would allow to assess the implications of major changes in Swiss electricity production and precisely simulate how the electricity sector could scale up if the electricity demand increases. This might be particularly useful if the transport sector would also switch toward the use of electricity.

The transport sector

In the first two chapters, the transport sector has a limited substitution potential as it is fueled solely by petroleum products and road and rail transport are aggregated. The disaggregation of the transport sector and the coupling with MARKAL-CHTRA performed in the third chapter were expected to increase the flexibility of the sector. Nevertheless, the third chapter I find that the transport sector remained relatively inelastic to CO_2 taxation. This somehow unexpected result is mainly the consequence of the limited number of personal car types in the bottom-up model. Indeed, if it seems realistic that hydrogen cars would not play a major role by 2030, it is expected that plug-in hybrid and electric cars could represent a significant share if the car fleet in the medium term. The addition of

a greater number of personal car types, in particular plug-in hybrids and electric cars, could be a valuable improvement to the model presented in chapter 3.

Acceptability

By showing the costs of climate policies for the Swiss economy and the impacts on the various economic sectors, this thesis already contributes to the question of the acceptability of climate policies. More specifically, in the third chapter, it compares the policies devised as a result of a consultation procedure with the economy and the society to the implementation of an equivalent uniform tax and presents the additional welfare impacts that can be attributed to the efforts of rendering the policies acceptable.

An hybrid model such as the one used in the third chapter could be further developed to investigate climate policies accounting for both acceptability and efficiency, in particular through the analysis of various redistribution schemes as proposed by Baranzini et al. (2000). Furthermore, the inclusion of multiple households in the CGE model types would render such an analysis increasingly policy relevant.

Appendix A

Appendix to Chapter 1

A.1 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:

$$HCRES_r \cdot \theta_r^{res\,t} = HCT_r \cdot \lambda_r^{hct} \cdot \alpha_r^{res} \cdot \left[\frac{PCT_r}{PCRES_r \cdot \lambda_r^{hct} \cdot \theta_r^{res\,t}} \right]^{\sigma_r^{hc}}, \qquad \text{(A.1)}$$

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 ($HCRESE$) is calculated as:

$$HCRESE_r \cdot \theta_r^{rese\,t} = HCRES_r \cdot \lambda_r^{hcres} \cdot \alpha_r^{rese} \cdot \left[\frac{PCRES_r}{PCRESE_r \cdot \lambda_r^{hcres} \cdot \theta_r^{rese\,t}}\right]^{\sigma_r^{hres}}, \tag{A.2}$$

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

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

$$HC_{17,r}^{res} \cdot \theta_r^{res17\,t} = HCRES_r \cdot \lambda_r^{hcres} \cdot (1 - \alpha_r^{rese}) \cdot \left[\frac{PCRES_r}{PC_{17\,r} \cdot \lambda_r^{hcres} \cdot \theta_r^{res17\,t}}\right]^{\sigma_r^{hres}}, \tag{A.3}$$

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:

$$HC_{i\,r}^{res} = HCRESE_r \cdot \lambda_r^{hcrese} \cdot \alpha_{i\,r}^{resee} \cdot \left[\frac{PCRESE_r}{PC_{i\,r} \cdot \lambda_r^{hcres}}\right]^{\sigma_r^{hrese}}, \forall i = 1, \ldots, 5, \tag{A.4}$$

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

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:

$$HC_{i\,r} = HC_{i\,r}^{res} + HC_{i\,r}^{tra}, \forall i = 1, \ldots, 5, \tag{A.5}$$

$$HC_{17\,r} = HC_{17\,r}^{res} + HC_{17\,r}^{oth}. \tag{A.6}$$

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

$$PCRES_r = \lambda_r^{res} \cdot \left[\alpha_r^{rese} \cdot \left(\frac{PCRESE_r}{\theta_r^{rese\,t}} \right)^{1-\sigma_r^{res}} + (1-\alpha_r^{rese}) \cdot \left(\frac{PC_{17\,r}}{\theta_r^{res17\,t}} \right)^{1-\sigma_r^{res}} \right]^{\frac{1}{1-\sigma_r^{res}}}, \tag{A.7}$$

$$PCRESE_r = \lambda_r^{rese} \cdot \left[\sum_{i=1,\ldots,5} \alpha_{i\,r}^{resee} \cdot PC_{i\,r}^{1-\sigma_r^{rese}} \right]^{\frac{1}{1-\sigma_r^{rese}}}. \tag{A.8}$$

Appendix B

Appendix to Chapter 2

B.1 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 = Σ_ij |ΔPE_ij|
if crit_PE > 0.01 then call RunMG;
crit = e − e · t_max/p_W − ē;
crit_d = e − ē_d;
```

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

```
Input: Total target on Swiss emissions ē
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 |Δtax| > 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 ē, Minimal target on Swiss domestic emissions
       ē_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 ≤ 0 and crit > 0 then
        target = t; criteria = e − rev/p_W − ē;
    else if crit_d > 0 and crit ≤ 0 then
        target = d; criteria = e − ē_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 ≤ 0 and crit > 0 then
        target = t; criteria = e − rev/p_W − ē;
    else if crit_d > 0 and crit ≤ 0 then
        target = d; criteria = e − ē_d;
    end
end
while |criteria| > 0.01 and |Δtax| > 0.001 do
    call RunMG;
    if target = t then
        criteria = e − e · tax/p_W − ē;
    else
        criteria = e − ē_d;
    end
    if criteria < 0 then t_max = tax else t_min = tax;
    tax = t_min + (t_max − t_min)/2;
end
```

B.2 Equations in the residential nest

(See section A.1)

B.3 Characteristics of the models

TableB.1 presents the regional and sectoral dimensions of GEMINI-E3, as well as the sectoral aggregation used in this paper. TableB.2 shows the useful demands in MARKAL-CHRES.

Table B.1: Dimensions of the complete and aggregated GEMINI-E3 model

Countries and Regions			Sectors/Products
Annex B			***Energy***
Germany	DEU	EUR	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	OEU	10 Metal and metal products
Russia	RUS		11 Paper Products Publishing
Rest of Former Soviet Union	XSU		12 Transport n.e.c.
United States of America	USA	OEC	13 Sea Transport
Canada	CAN		14 Air Transport
USA Australia and New Zealand	AUZ		15 Consuming goods
Japan	JAP		16 Equipment goods
Non-Annex B			17 Services
China	CHI	DCS	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 B.2: 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

Appendix C

Appendix to Chapter 3

C.1 Characteristics of the models

Table C.1 presents the regional and sectoral dimensions of GEMINI-E3, as well as the sectoral aggregation used in this paper. For additional information regarding the GEMINI-E3 model, such as the list of GHG emissions calculated by the model, see Bernard and Vielle (2008). Table C.2 presented the values of the elasticity parameters in both production and consumption functions. Tables C.3 and C.4 show the useful demands in MARKAL-CHRES.

Table C.1: Dimensions of the complete and aggregated GEMINI-E3 model

(See table B.1)

C.2 Amendments to the standard GEMINI-E3 model

We have modified the equations related to international trade and international transport margins, allowing for the disaggregation of imports and trade margins and the aggregation of exports. In the following equations, i indexes the 29 sectors in Switzerland (CHE) whereas j is the index of the 18 sectors used in all other regions (r). The sectors $12a, \ldots, 12h$ are aggregated into sector 12 and sectors $17a, \ldots, 17e$ are aggregated into sector 17.

Table C.2: GEMINI-E3 elasticities

Production function			Consumption function		
				Value	
Parameter	Sector	Value	Parameter	CHE	other regions
all regions			σ^{hc}	0.20	0.50
σ	All	0.30	σ^{hres}	0.00	0.80
σ^{pf}	01	0.40	σ^{htra}	0.10	0.50
	02, 03	0.20	σ^{hoth}	0.30	0.30
	04	0.10	σ^{hrese}	0.00	
σ^{pp}	All	0.10	σ^{htrag}	0.80	-
σ^{e}	01 to 05	0.10	σ^{htrap}	0.50	0.50
	06,07,12,13,14	0.20	σ^{htrapp}	0.50	-
	Others	0.40	σ^{htrapo}	0.30	-
σ^{fe}	01 to 04	0.10	$\sigma^{htrapoo}$	0.30	-
	05	1.50	$\sigma^{htrapooe}$	0.00	-
	06 to 11 & 15 to 18	0.90	σ^{htrao}	-	0.30
	Others	0.30	σ^{htraoe}	-	0.80
σ^{r}	All	0.60			
σ^{m}	All	0.20			
σ^{x}	01,03	2.00			
	2	10.00			
	5	0.50			
	12,13,14,17	0.10			
	18	0.05			
	Others	3.00			
σ^{mm}	All	0.20			
only for Switzerland					
σ^{t}	All	0.10			
σ^{r}	All	0.10			
σ^{rp}	All	0.80			
σ^{rg}	All	0.80			

Table C.3: MARKAL-CHRES demand segments

(See table B.2)

Table C.4: MARKAL-CHTRA demand segments

TAD	Domestic Aviation
TAI	International Aviation
TRB	Road Bus
TRC	Road Commercial Trucks
TRE	Road Three Wheels
TRH	Road Heavy Trucks
TRL	Road Light Vehicle
TRM	Road Medium Trucks
TRT	Road Auto
TRW	Road Two Wheels
TTF	Rail-Freight
TTP	Rail-Passengers
TWD	Domestic Internal Navigation
TWI	International Navigation

As in the standard GEMINI-E3, imports (M_{ir}) are computed from total demand according to the Armington assumption (Armington, 1969):

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

where σ^x_{iCHE}, α^x_{iCHE} and λ^x_{iCHE} represent the CES parameters, respectively the elasticity of substitution, the share parameter and the technology shifter, PY_{iCHE} is the price of composite good, PI_{iCHE} the price of import and κ^i_{iCHE} the duty rate. The import prices are defined as follows:

$$PI_{iCHE} = \lambda^i_{iCHE} \cdot \left[\sum_r \alpha^i_{irCHE} \cdot \left[\sum_j (\Phi_{jirCHE} \cdot PX_{jr} \cdot (e_r / e_{CHE})) \right]^{1-\sigma^i_{iCHE}} \right]^{\frac{1}{1-\sigma^i_{iCHE}}} \quad \text{(C.2)}$$

with PX_{jr} being the price of exports of the aggregate good j, e_r is the exchange

rate and Φ an aggregation/dissaggregation matrix of the form:

$$\Phi_{jirCHE} = \begin{bmatrix} 1 & & & & & & & & & \\ & \ddots & & & & & & & & \\ & & 1 & & & & & 0 & & \\ & & & \underbrace{1 \cdots 1}_{12a \cdots 12g} & & & & & & \\ & & & & 1 & & & & & \\ & & & & & \ddots & & & & \\ & & 0 & & & & 1 & & & \\ & & & & & & & \underbrace{1 \cdots 1}_{17a \cdots 17e} & & \\ & & & & & & & & 1 & \end{bmatrix} \tag{C.3}$$

$$\Phi_{ijCHEr} = \begin{bmatrix} 1 & & & & & & & & & \\ & \ddots & & & & & & & & \\ & & 1 & & & & & & & \\ & & & \phi_{12a} & & & & & & \\ & & & \vdots & & & & 0 & & \\ & & & \phi_{12g} & & & & & & \\ & & & & 1 & & & & & \\ & & & & & \ddots & & & & \\ & & & & & & 1 & & & \\ & & & & & & & \phi_{17a} & & \\ & & 0 & & & & & \vdots & & \\ & & & & & & & \phi_{17e} & & \\ & & & & & & & & 1 & \end{bmatrix} \tag{C.4}$$

ϕ_{12x} and ϕ_{17x} being the shares of exports of the various new sectors over the original sectors 12 and 17.

Imports are then computed by origins (MR_{iCHEr}) with an another CES func-

tion:

$$MR_{iCHEr} = M_{iCHE} \cdot \lambda^i_{iCHE} \cdot \alpha^i_{iCHEr} \cdot \left[\frac{PI_{iCHE}}{\lambda^i_{iCHE} \sum_j (\Phi_{jirCHE} \cdot PX_{jr} \cdot (e_r/e_{CHE}))} \right]^{\sigma^i_{ir}} \tag{C.5}$$

.

Exports are calculated as follows:

$$EX_{iCHE} = \sum_h MR_{iCHEh} \tag{C.6}$$

and the price of Swiss exports on the international market are calculated with the following formula:

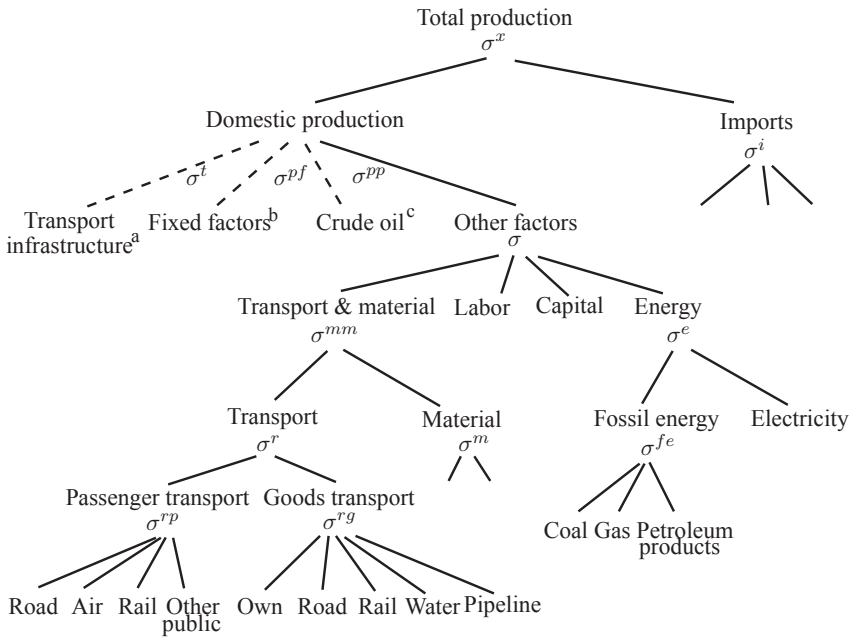
$$PX_{jCHE} = \sum_i (\Phi_{ijCHEr} \cdot PB_{iCHE} \cdot (1 + \kappa^x_{iCHE})) \tag{C.7}$$

.

C.2.1 Revised production functions

As explained in chapter 3.2.1, the Swiss transport sector has been disaggregated for the sake of this analysis and in order to allow for the coupling with a bottom-up model. Consequently, the Swiss CES production function is slightly different from those in the other regions (see Bernard and Vielle, 2008). Figure C.1 presents the Swiss nested CES production function. The σ^x refer to the elasticity parameter of each node (values can be found in table C.2 and in Bernard and Vielle, 2008). The major differences between these nested CES functions and those used for other regions are, firstly, the presence of the infrastructure at the top level for the transport sectors, secondly, the disaggregation of transport into passenger and freight transport and, thirdly, the detailed disaggregation of the freight and passenger transport nest.

In the mathematical formulation, the following equations have to be modified or included in the model. For the Swiss transport sectors, other than the infrastructure sectors, the domestic production (XDT_{iCHE}) is equal to



[a] Present only in the production functions of transport sectors with the infrastructure corresponding to the mode of transport, i.e. sector 12a for sectors 12b, 12c and 12d; sector 17b for sector 13; sector 17c for sector 14 and sector 17d for sectors 12e, 12f and 12g.
[b] Present only in the production functions of sectors 01, 02 and 03.
[c] Present only in the production function of sector 04.

Figure C.1: Structure of the Swiss nested CES production function

$$XDT_{iCHE} = Y_{iCHE} \cdot \lambda^x_{iCHE} \cdot \alpha^x_{iCHE} \cdot \left[\frac{PY_{iCHE}}{\lambda^x_{iCHE} \cdot PDT_{iCHE}} \right]^{\sigma^x_{iCHE}} , \forall i = 12b, 12c, 12d, 13, 14, 12e, 12f, 12h \tag{C.8}$$

where the variables and parameters are the same as in equation C.1. Then, the domestic production of transport sectors is separated in the intermediate consumption of the relevant infrastructure (IC_{ikCHE}, with k=12a,16c,16a and 16b) and an aggregate of other inputs (X_{ir}) through other CES functions, which vary slightly according to the mode of transport.

The infrastructure intermediate consumption is calculated as:

$$IC_{ikCHE} = XDT_{iCHE} \cdot \lambda^{pi}_{iCHE} \cdot (1 - \alpha^{pi}_{iCHE}) \cdot \left[\frac{PDT_{iCHE}}{\lambda^{pi}_{iCHE} \cdot PIC_{12aCHE}} \right]^{\sigma^{pi}_{iCHE}}$$
$$, \forall i = 12b, 12c, 12d, 12e, 12f, 12h, 13, 14 \quad \text{(C.9)}$$

with $k = 12a$ for $i = 12b, 12c, 12d$, $k = 16c$ for $i = 12e, 12f, 12h$, $k = 16a$ for $i = 13$ and $k = 16b$ for $i = 14$.

The consumption of other inputs (X_{ir}) is equal to:

$$X_{iCHE} = XT_{iCHE} \cdot \lambda^{pi}_{iCHE} \cdot \alpha^{pi}_{iCHE} \cdot \left[\frac{PDT_{iCHE}}{\lambda^{pi}_{iCHE} \cdot PD_{iCHE}} \right]^{\sigma^{pi}_{iCHE}}$$
$$, \forall i = 12b, 12c, 12d, 13, 14, 12e, 12f, 12h. \quad \text{(C.10)}$$

PDT_{ir} is the price of domestic production for sectors 12b,12c,12d,13,14,12e,12f and 12h, PIC_{iCHE} the price of the intermediate consumptions of the relevant infrastructure sector, and PD_{iCHE} the price of other inputs. PDT_{iCHE} is therefore calculated as follows:

$$PDT_{iCHE} = \lambda^{pi}_{iCHE} \cdot \Big[\alpha^{pi}_{iCHE} \cdot PD^{1-\sigma^{pi}_{iCHE}}_{iCHE} +$$
$$+ (1 - \alpha^{pi}_{iCHE}) \cdot PIC^{1-\sigma^{pi}_{iCHE}}_{ikCHE} \Big]^{\frac{1}{1-\sigma^{pi}_{iCHE}}}$$
$$, \forall i = 12b, 12c, 12d, 13, 14, 12e, 12f, 12h \quad \text{(C.11)}$$

with the index k refereing to the infrastructure sector relevant for the mode of transport.

The second difference, is at the level of the transport nest itself, where for all regions the aggregated transport (TR_{ir}) is split into sectors 12 to 14, whereas for Switzerland we first differentiate between passenger and goods transport using

the following CES functions:

$$PATR_{iCHE} = TR_{iCHE} \cdot \lambda^{r}_{iCHE} \cdot \alpha^{r}_{iCHE} \cdot \left[\frac{PTR_{iCHEr}}{\lambda^{r}_{iCHE} \cdot PPATR_{iCHE}\cdot} \right]^{\sigma^{r}_{iCHE}} \quad \text{(C.12)}$$

$$GOTR_{iCHE} = TR_{iCHE} \cdot \lambda^{r}_{iCHE} \cdot (1 - \alpha^{r}_{iCHE}) \cdot \left[\frac{PTR_{iCHEr}}{\lambda^{r}_{iCHE} \cdot PGOTR_{iCHE}\cdot} \right]^{\sigma^{r}_{iCHE}} \quad \text{(C.13)}$$

The prices of the various nests are calculated as follows:

$$PTR_{iCHE} = \lambda^{r}_{iCHE} \cdot \Big[\alpha^{r}_{kiCHE} \cdot PPATR^{1-\sigma^{r}_{iCHE}}_{kiCHE} + (1 - \alpha^{r}_{kiCHE}) \cdot PGOTR^{1-\sigma^{r}_{iCHE}}_{kiCHE} \Big]^{\frac{1}{1-\sigma^{r}_{iCHE}}} \quad \text{(C.14)}$$

$$PPATR_{iCHE} = \lambda^{rp}_{iCHE} \cdot \left[\sum_{k=12b,12d,12e,14} \alpha^{rp}_{kiCHE} \cdot PIC^{1-\sigma^{rp}_{iCHE}}_{kiCHE} \right]^{\frac{1}{1-\sigma^{rp}_{iCHE}}} \quad \text{(C.15)}$$

$$PGOTR_{iCHE} = \lambda^{rp}_{iCHE} \cdot \left[\sum_{k=12c,12f,12g,12h,13} \alpha^{rp}_{kiCHE} \cdot PIC^{1-\sigma^{rp}_{iCHE}}_{kiCHE} \right]^{\frac{1}{1-\sigma^{rp}_{iCHE}}} \quad \text{(C.16)}$$

Finally, the goods and passenger transport sectors are allocated to the new transport sectors with the following formulas:

$$IC_{kiCHE} = PATR_{iCHE} \cdot \lambda^{rp}_{iCHE} \cdot \alpha^{rp}_{kiCHE} \cdot \left[\frac{PPATR_{iCHE}}{\lambda^{rp}_{iCHE} \cdot PIC_{kiCHE}\cdot} \right]^{\sigma^{rp}_{iCHE}} \quad \forall k = 12b, 12d, 12e, 14 \quad \text{(C.17)}$$

$$IC_{kiCHE} = GOTR_{iCHE} \cdot \lambda^{rg}_{iCHE} \cdot \alpha^{rg}_{kiCHE} \cdot \left[\frac{PGOTR_{iCHE}}{\lambda^{rg}_{iCHE} \cdot PIC_{kiCHE}\cdot} \right]^{\sigma^{rg}_{iCHE}} \quad \forall k = 12c, 12f, 12g, 12h, 13 \quad \text{(C.18)}$$

C.2.2 Revised final consumption

Figure C.2 presents the Swiss nested CES utility function. Similarly to the production function, it differs from other regions at the level of the transportation sectors in view of the increased disaggregation of the transport sectors in Switzerland. First, the transport consumption is composed of passenger and goods transport. Secondly, the passenger transport is either private or purchased. Thirdly, the private transportation, i.e. private cars, is separated in consumption of road infrastructure and other goods and services, namely equipments and energy. Finally, goods transport, purchased passenger transport and energy used in transport are aggregates of sectors {12b,12d,12e,14}, {12c,12f,12g,13} and {3,4,5} respectively.

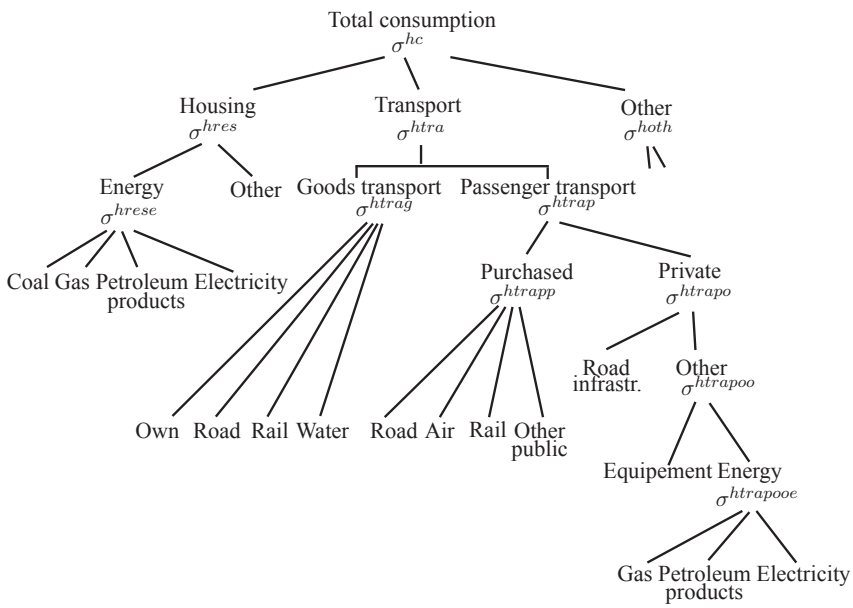


Figure C.2: Structure of the households' nested CES utility function

The residential side of the households' consumption is calculated as in Sceia et al. (2009a) but the transport nest is calculated as follows.

The consumption of the transportation aggregated good ($HCTRA$) equals:

$$HCTRA_{CHE} \cdot {\theta_{CHE}^{hct}}^{t} = HCT_{CHE} \cdot \lambda_{CHE}^{hct} \cdot \alpha_{CHE}^{hct} \cdot \left[\frac{PCT_{CHE}}{PCTRA_r \cdot \lambda_{CHE}^{hct} \cdot {\theta_{CHE}^{hct}}^{t}} \right]^{\sigma_{CHE}^{hc}}, \tag{C.19}$$

where θ_r^{hct} is the technical progress of the transport nest, HCT the total aggregated consumption, PCT the price of the aggregated consumption and $PCTRA$ the price of the transport aggregated good.

The consumption of the aggregated goods transport ($HCTRAG$) and aggregated passenger transport ($HCTRAP$) are calculated as:

$$HCTRAG_{CHE} \cdot {\theta_{CHE}^{htrag}}^{t} = HCTRA_{CHE} \cdot \lambda_{CHE}^{htra} \cdot \alpha_{CHE}^{htra} \cdot \left[\frac{PCTRA_{CHE}}{PCTRAG_{CHE} \cdot \lambda_{CHE}^{htra} \cdot {\theta_{CHE}^{htrag}}^{t}} \right]^{\sigma_{CHE}^{htra}}, \tag{C.20}$$

$$HCTRAP_{CHE} \cdot {\theta_{CHE}^{htrag}}^{t} = HCTRA_{CHE} \cdot \lambda_{CHE}^{htra} \cdot (1 - \alpha_{CHE}^{htra}) \cdot \left[\frac{PCTRA_{CHE}}{PCTRAP_{CHE} \cdot \lambda_{CHE}^{htra} \cdot {\theta_{CHE}^{htrag}}^{t}} \right]^{\sigma_{CHE}^{htra}}, \tag{C.21}$$

where θ_{CHE}^{htrag} is the technical progress of the goods transport nest, θ_{CHE}^{htrap} the technical progresses of the passenger transport nest, and $PCTRAG_{CHE}$ is the price of the goods transport aggregated good and $PCTRAG_{CHE}$ the price of the passenger transport aggregated good. The aggregated goods transport is disaggregated into the consumption of the various sectors assumed to undertake only goods transport, i.e. 13, 12c, 12f, 12g and 12h, using the following formula.

$$HC_{iCHE} = HCTRAG_{CHE} \cdot \lambda_{CHE}^{htrag} \cdot \alpha_{C}^{htrag} HE \cdot \left[\frac{PCTRAG_{CHE}}{PC_{iCHE} \cdot \lambda_{CHE}^{htrag}} \right]^{\sigma_{CHE}^{htrag}}, \forall i = 13, 12c, 12f, 12g, 12h, \tag{C.22}$$

The aggregated passenger transport is separated into purchased and own passenger transport:

$$HCTRAPP_{CHE} \cdot \theta_{CHE}^{htrag\,t} = HCTRAP_{CHE} \cdot \lambda_{CHE}^{htrag} \cdot \alpha_{CHE}^{htrag} \cdot \left[\frac{PCTRAP_{CHE}}{PCTRAPP_{CHE} \cdot \lambda_{CHE}^{htrag} \cdot \theta_{CHE}^{htrag\,t}}\right]^{\sigma_{CHE}^{htrag}}, \tag{C.23}$$

$$HCTRAPO_{CHE} \cdot \theta_{CHE}^{htrag\,t} = HCTRA_{CHE} \cdot \lambda_{CHE}^{htrag} \cdot (1 - \alpha_{CHE}^{htrag}) \cdot \left[\frac{PCTRAP_{CHE}}{PCTRAPO_{CHE} \cdot \lambda_{CHE}^{htrag} \cdot \theta_{CHE}^{htrag\,t}}\right]^{\sigma_{CHE}^{htrag}}, \tag{C.24}$$

with $PCTRAPP_{CHE}$ and $PCTRAPO_{CHE}$ the prices of the aggregated purchased passenger transport and own passenger transport goods. The latter is disaggregated into the consumption of the various sectors assumed to undertake solely passenger transport, i.e. 14, 12b, 12d and 12e.

$$HC_{iCHE} = HCTRAPP_{CHE} \cdot \lambda_{CHE}^{htrapp} \cdot \alpha_{iCHE}^{htrapp} \cdot \left[\frac{PCTRAPP_{CHE}}{PC_{iCHE} \cdot \lambda_{CHE}^{htrapp}}\right]^{\sigma_{CHE}^{htrapp}}, \forall i = 14, 12b, 12d, 12e, \tag{C.25}$$

The other purchased transport is then further disaggregated in line with the following formulas:

$$HC_{17d,CHE} \cdot \theta_r^{17d\,CHE} = HCTRAPO_{CHE} \cdot \lambda_{CHE}^{htrapo} \cdot (\alpha_{CHE}^{htrapo}) \cdot \left[\frac{PCTRAPO_{CHE}}{PC_{17dCHE} \cdot \lambda_r^{hptrapo} \cdot \theta_{CHE}^{17d\;t}}\right]^{\sigma_{CHE}^{htrapo}}, \tag{C.26}$$

$$HCTRAPOO_{CHE} \cdot \theta_{CHE}^{htrapoo\,t} = HCTRAPO_{CHE} \cdot \lambda_{CHE}^{htrapo} \cdot (1 - \alpha_{CHE}^{htrapo}) \cdot \left[\frac{PCTRAPO_{CHE}}{PCTRAPOO_{CHE} \cdot \lambda_{CHE}^{htrapo} \cdot \theta_{CHE}^{htrapoo\,t}}\right]^{\sigma_{CHE}^{htrapo}}, \quad \text{(C.27)}$$

$$HC_{16,CHE}^{tra} \cdot \theta_{r}^{tra16\,CHE} = HCTRAPOO_{CHE} \cdot \lambda_{CHE}^{htrapoo} \cdot (\alpha_{CHE}^{htrapoo}) \cdot \left[\frac{PCTRAPOO_{CHE}}{PC_{16\,CHE} \cdot \lambda_{r}^{hptrapoo} \cdot \theta_{CHE}^{tra16\,t}}\right]^{\sigma_{CHE}^{htrapoo}}, \quad \text{(C.28)}$$

$$HCTRAPOE_{CHE} \cdot \theta_{CHE}^{htrapoo\,t} = HCTRAPOO_{CHE} \cdot \lambda_{CHE}^{htrapoo} \cdot (1 - \alpha_{CHE}^{htrapoo}) \cdot \left[\frac{PCTRAPOO_{CHE}}{PCTRAPOE_{CHE} \cdot \lambda_{CHE}^{htrapoo} \cdot \theta_{CHE}^{htrapoe\,t}}\right]^{\sigma_{CHE}^{htrapoo}}, \quad \text{(C.29)}$$

Moreover, the households transportation consumption of energies (HC_{iCHE}^{tra}) is calculated as:

$$HC_{iCHE}^{tra} = HCTRAPOE_{CHE} \cdot \lambda_{CHE}^{htrapooe} \cdot \alpha_{ir}^{htrapooe} \cdot \left[\frac{PCTRAPOE_{r}}{PC_{iCHE} \cdot \lambda_{CHE}^{htrapooe}}\right]^{\sigma_{CHE}^{htrapooe}}, \forall i = 1, \ldots, 5, \quad \text{(C.30)}$$

Furthermore, the transportation 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:

$$HC_{ir} = HC_{ir}^{res} + HC_{ir}^{tra}, \forall i = 1, \ldots, 5, \quad \text{(C.31)}$$

$$HC_{16\,CHE} = HC_{16\,r}^{tra} + HC_{16\,r}^{oth}. \quad \text{(C.32)}$$

Finally, prices are calculated using the same parameters, in line with standard nested CES functions.

C.3 Welfare costs

Similarly to other general equilibrium models, GEMINI-E3 assesses the welfare costs of policies through the measurement of the classical Dupuit's surplus, i.e. in the modern formulation the Equivalent Variation of Income (EVI) or the Compensating Variation of Income (CVI). It is well acknowledged that surplus is to be preferred to changes in GDP or changes in Households' Final Consumption because these aggregates are measured at constant prices, according to the methods of National Accounting, and do not capture a main effect of climate change policies that is the change in the structure of prices. Moreover, it is highly informative to split the welfare costs in its three components: the Deadweight Loss of Taxation (DWL), the Gains from Terms of Trade (GTT) and the net revenue resulting from the trade of of emission certificates (CE).

Decomposition of the welfare costs is a complex issue that has been addressed in the literature, mainly by Böhringer and Rutherford (2002, 2004) in the case of climate change policy, and by Harrison et al. (2000) in a more general framework. In this study, we aim at an approximate decomposition providing for a general idea of the relative importance of each component. This is justified by the fact that the changes in prices, in particular the prices of foreign trade, are fairly small. Table C.5 presents the various steps allowing for the decomposition. In practice, we first calculate the surplus in line with the specification of the utility function. Then we approximate the GTT and calculate CE, to finally obtain the DWL by difference between the welfare gains and GTT plus CE[1].

[1]Calculation of the DWL is required in order to determine the true marginal cost of abatement (i.e. the welfare loss for a unit additional abatement). This marginal cost of abatement differs from the one usually represented in marginal abatement curves, which in fact represents the carbon tax associated to each level of abatement, when there are distortions (fiscal or economic) in the economy.

Table C.5: Measurement and components of welfare

$S = R - \triangle CVI$
Total Welfare Gain = Variation of income - Compensative Variation of Income
$= -DWL + GTT + CE$
= -Deadweight Loss of Taxation + Gains from Terms of Trade + Net Trade of Certificates
$GTT = \sum Exp_0 \triangle Pexp - \sum Imp_0 \triangle Pimp$

C.4 Coupling algorithms

The algorithms below use the the following nomenclature:

MARKAL variables

fm^r	residential fuel mix
ai^r	residential annualized investments
inv^r	residential investments considered for the building improvement program
fm^t	transport fuel mix
ai^t	transport annualized investments
fm^r_b	baseline residential fuel mix
ai^r_b	baseline residential annualized investments
inv^r_b	baseline residential investments considered for the building improvement program
$invc^r_b$	baseline residential investments costs considered for the building improvement program
fm^t_b	baseline transport fuel mix
ai^t_b	baseline transport annualized investments

GEMINI-E3 variables

PE	energy prices
DE	transport demand
BU	Budget of the residential building improvement program
tax^r	Swiss residential CO_2 tax vector
tax^t	Swiss transport CO_2 tax (levy) vector
tax_0^r	Swiss residential CO_2 tax vector from previous iteration
tax_0^t	Swiss transport CO_2 tax (levy) vector from previous iteration

Coupling module variables

ψ	Discount on technologies considered for the building improvement program
$M^r()$	run of MARKAL-CHRES
$M^t()$	run of MARKAL-CHTRA
$G()$	run of GEMINI-E3
$criteria$	convergence criteria
ξ	"smoothing" parameter
$\widetilde{tax^r}$	"Smoothed" Swiss residential CO_2 tax vector
$\widetilde{tax^t}$	"Smoothed" Swiss transport CO_2 tax (levy) vector

Algorithm 4: GMC-3.0 "Smoothed" coupling procedure

$(tax^r, tax^t, DE, PE, BU) = G(fm^r_b, ai^r_b, fm^t_b, ai^t_b)$;
$\psi = 0$; $criteria = 1$;
$fm^r, ai^r, inv^r) = M^r(tax^r, PE, \psi)$;
$fm^t, ai^t) = M^t(tax^t, DE, PE)$;
while $criteria > 0.01$ **do**
  $tax^r_0 = tax^r$;
  $tax^t_0 = tax^t$;
  $(tax^r, tax^t, DE, PE, BU) = G(fm^r, ai^r, fm^t, ai^t)$;
  $\widetilde{tax^r} = \xi \cdot tax^r + (1 - \xi) \cdot tax^r_0$;
  $\widetilde{tax^r} = \xi \cdot tax^t + (1 - \xi) \cdot tax^t_0$;
  $(fm^r, ai^r, inv^r) = M^r(\widetilde{tax^r}, PE, \psi)$;
  $(fm^t, ai^t) = M^t(\widetilde{tax^t}, DE, PE)$;
  call optBU;
  $criteria = i \times abs(tax^r - tax^r_0) + i \times abs(tax^t - tax^t_0)$;
end

Algorithm 5: Procedure - optBU

$\psi_{min} = 0$; $\psi_{max} = 1$;
while $abs(BU - (inv^r \cdot (invc^r_b - inv^r_b) \cdot \psi)) > 0.01$ **do**
  $\psi = \psi_{min} + (\psi_{max} - \psi_{min})/2$;
  $(fm^r, ai^r, inv^r) = M^r(\widetilde{tax^r}, PE, \psi)$;
  if $BU - (inv^r \cdot (invc^r_b - inv^r_b) \cdot \psi) < 0$ **then**
    $\psi_{max} = \psi$
  else
    $\psi_{min} = \psi$

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Occupational field

Economics & ICT

Work experience

2002-Present	IT Expert (half-time from 2005 to 2009) United Nations Economic Commission for Europe - Transport Division - TIR Secretariat
2005-2009	Assistant / Researcher (half-time) École Polytechnique Fédérale de Lausanne - REME
2001	Statistician United Nations Economic Commission for Europe - Transport Division
2000	Consultant United Nations Economic Commission for Europe - Transport Division - TIR secretariat
2000	Consultant WorldTempus.com
1999-2000	Consultant United Nations Economic Commission for Europe - Trade Division - Timber Section
1997-1999	Assistant statistician (part-time) United Nations Economic Commission for Europe - Statistical Division
1992-1996	IT Analyst and programmer Department of Public Economy - Etat de Genève

Education and training

2005 - 2009	Environment Doctoral Program École Polytechnique Federale de Lausanne
1999	**Diplôme d'études supérieures en économétrie**
1997	**Licence es sciences économiques orientation économétrie appliquée**
1994 - 1999	Department of Econometrics Université de Genève
1993	**Brevet fédéral d'analyste-programmeur**
1992	**Diplôme de programmeur analyste**
1991 - 1993	Formation de programmeur Analyste Ecole supérieure de commerce de Malagnou, Geneva
1991	**Certificat de maturité scientifique, with distinction 'mention bien'**
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1987-1991	Collège Calvin, Geneva Section Scientifique

Publications

2010 *"Tree steps toward modeling Swiss post-2012 Climate policies"*, A. Sceia, PhD Thesis, EPFL.

2009 *"Assessment of acceptable Swiss post-2012 climate policies"*, A. Sceia, J.-C. Altamirano, M. Vielle and N. Weidmann, NCCR working paper and submitted to Climate Policy.

2009 *"Sustainability, neutrality and beyond in the framework of Swiss post-2012 climate policy"*, A. Sceia, J.-C. Altamirano, T. F. Schulz and M. Vielle, NCCR working paper and under review at the Journal of Policy Modeling.

2008 *"Integrated Assessment of Swiss GHG Mitigation Policies After 2012 – Focus on the Residential Sector"* A. Sceia, J.-C. Altamirano, L. Drouet, T.F. Schulz and M. Vielle, NCCR working paper and submitted to Environmental Modeling and Assessment.

1999 *"Méthodes pour la sélection de modèles linéaires par validation croisée"*, A. Sceia, Master Thesis, University of Geneva.

Extra curricular activities

2009 - Present Committee member and captain for the International Golf Club

Personal skills and competencies

ICT

Systems: Windows, MacOSX

Databases: SQLServer, MSAccess, MySQL

Programming: GAMS, MATLAB, SQL, VisualBasic

Scientific software: S-Plus, R, TSP, Eviews

Other: Latex, MS Office, Photoshop, Visio,. . .

Organizational skills and competencies: Project management (MSProject)

Mother tongue(s): **French**

Other language(s): English (UN proficiency), Italian, Spanish (UN proficiency), German, Portuguese, Chinese

Self-assessment
European level(*)

	Understanding		Speaking		Writing
	Listening	Reading	Spoken interaction	Spoken production	
English	C1 Proficient user	C2 Proficient user	C1 Proficient user	C1 Proficient user	C1 Proficient user
Italian	C2 Proficient user	C1 Proficient user	C2 Proficient user	C1 Proficient user	C1 Proficient user
Spanish	C1 Proficient user	C1 Proficient user	C1 Proficient user	C1 Proficient user	C1 Proficient user
German	A2 Basic user	A2 Basic user	A2 Basic user	A2 Basic user	A2 Basic user
Portuguese	B1 Independent user	A2 Basic user	B1 Independent user	A2 Basic user	A2 Basic user
Chinese	A1 Basic user	A1 Basic user	A1 Basic user	A1 Basic user	A1 Basic user

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Additional information

Personal interests: Golf, ski touring, fly fishing, hiking, jogging, traveling, billiard, chess, music, photography

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