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Assessment of acceptable Swiss post-2012 climate policies*

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Abstract

In the framework of the revision of the Swiss CO_2-Law and in view for the international negotiations that will take place at the next 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 at the beginning of 2009 and has allowed major stakeholders and lobbies to defend their interests. Using a hybrid model, we evaluate 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

JEL Codes: C68, D58, Q54, N70

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1 Introduction

In the framework of the revision of the Swiss CO_2-Law and in view for the international negotiations that will take place at the next 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 4.

In order to adequately evaluate the future Swiss climate policies, model all the envisaged instruments and 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 model describing respectively the Swiss residential and transportation sectors. This paper continues the work undertaken earlier in Sceia et al. (2009) 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, environments and economy issues as no ideal solution has been recognized yet. Two main methods have been used to tackle the issue and are commonly refereed to as soft-link and hard-link methods. While the first keep 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 have used a soft-link method that is different from those found in other studies. Drouet et al. (2005) use a MARKAL model of the Swiss residential sector to complement a CGE model in which the residential 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 on of the models types. Examples include MARKAL-macro models, as used 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 a 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 2 presents the models and the coupling methodology, section 3 presents the baseline scenario, sections 4 and 5 present the policy scenarios and their respective results and section 6 concludes.

2 Methodology

2.1 GEMINI-E3

We use an aggregated version of GEMINI-E3, a dynamic-recursive CGE model with a highly detailed representation of indirect taxation, that represents the world economy in 6 regions and 18 sectors[1]. 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 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., 2009). 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).

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

[1]The complete GEMINI-E3 represents the world economy in 28 regions (including Switzerland) and 18 sectors (see table 12 in appendix A 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.

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 10 and 9. The complete and aggregated GEMINI-E3 dimensions are presented in appendix A table 12.

We have also included an international emission certificates market that allows 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).

2.1.1 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 1). The disaggregation affects two of the original sectors, i.e. "transport nec" (12) and "services" (17). The numbering of the new sectors allows to identify how the new transport sectors were originally aggregated.

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, for 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

Table 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

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 for 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 for the disaggregation of imports and trade margins and the aggregation of exports.

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 model has a time horizon from 2000 until 2050, divided into eleven time steps each representing a time period with a duration of five years. Both MARKAL-CHRES and MARKAL-CHTRA include 14 energy demand segments (see appendix A table 14 and 15)and use a 3.5% discount rate (**?**). 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 are calculated on the basis of GEMINI-E3 (see section 2.3).

2.3 Coupling

Compared to previous studies (Sceia et al., 2008, 2009), the coupling procedure allowing for linking the models has been amended to allow GEMINI-E3 to 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 1, until a defined threshold on the variation of the taxes is reached. The coupling procedure also takes into account a residential program which is paid by a part of the revenue of the CO_2 tax on heating fuels.

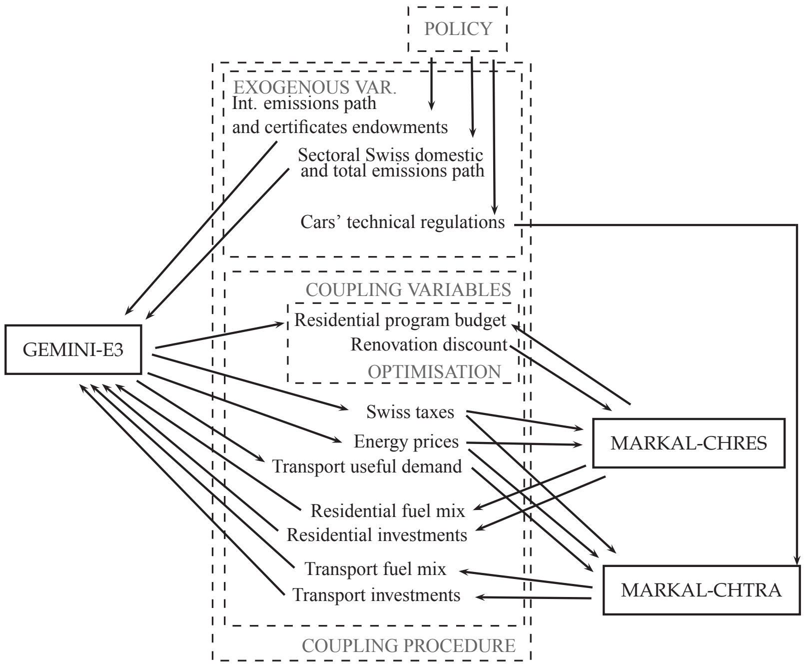

Figure 1: Coupling schema

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 Sceia et al. (2009), 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 for 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 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 links between the GEMINI-E3 sectors and the MARKAL-CHTRA demand segments (see table 2).

Table 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

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 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

Table 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 for 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

regions, they 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 2 presents the GHG emissions for each region until 2030.

Table 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 Products 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

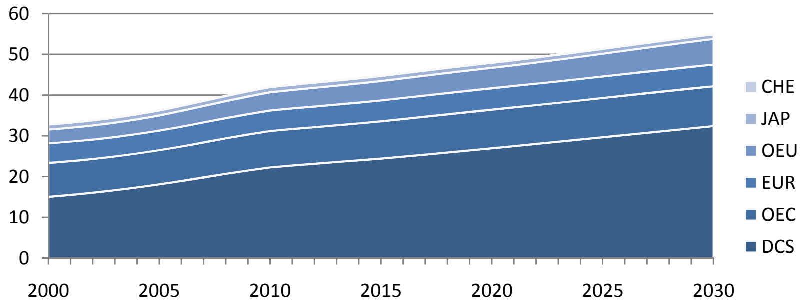

Figure 2: Baseline GHG emissions (GtCO_2eq)

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.

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.

4 Policy scenarios

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 4.2).

The envisaged Swiss post-Kyoto policies, described in detail in table 5, are

Table 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 $MtCO_2eq$

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.

4.1.1 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 allowed 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

Table 5: Swiss emissions targets (% of 1990 emissions)

	Scenario 1		Scenario 2	
	2020	2030	2020	2030
ETS[a]	-1.75 % p.a.		-2.9 % p.a.	
Certificates purchase cap[b]	40%		50%	
Transport[c]	-25%	-42%	-40%	-60%
Technical regulations on cars[d]	target on average emissions of new cars			
Combustible fuels[c]	-25%	-33%	-35%	-50%
Building improvement program[e](2010-2020)	200 Mio. CHF p.a. [f]			
Certificates purchase cap[c](% of 1990 GHG)	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 *standard* cars as of 2015
[e] Modeled as a discount on refurbishment costs (energy saving technologies)
[f] 130 Mio. USD_{2008}

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.

4.1.2 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, 2009). 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 descriptions of the available and future vehicles does not go into sufficient details 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.

4.1.3 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 economic sectors through social security[5]. The building improvement program

[4] 130 Mio. USD_{2008}

[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

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 for 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, at a shadow price of 191 USD_{2008}/tCO_2eq.

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 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 6. The "low" scenario is used to analyze the first Swiss scenario, where 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 and 4 show the international abatement targets for both scenarios.

For the sake of simplicity, we assume that all regions, except Switzerland,

modeled the redistribution of the tax as a simple lump-sum transfer.

Table 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

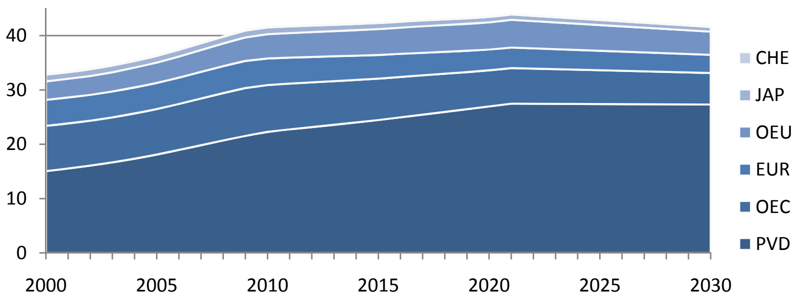

Figure 3: Scenario 1 GHG emissions targets ($GtCO_2eq$)

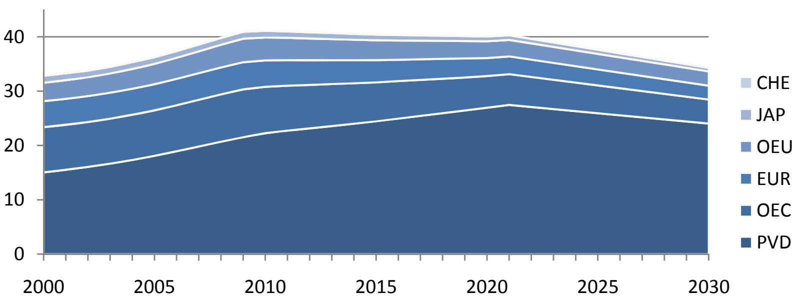

Figure 4: Scenario 2 GHG emissions targets ($GtCO_2eq$)

fully participate in a global emissions cap and trade system, allowing to equalize 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

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

to the baseline emissions in order to avoid that the overall effect of the policies is jeopardized by carbon leakage.

5 Results

5.1 Scenario 1

5.1.1 Carbon prices and emissions reductions

Tables 7 and 8 present respectively the taxes that allow to achieve the objectives and the detailed emission 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 124 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.

Table 7: Swiss environmental taxes and prices of certificates/allowances in scenario 1 (USD_{2008}/tCO_2eq)

	2013	2015	2020	2030
Transport fuels levy	0.05	0.14	0.60	3.31
Combustible fuels tax	37.77	55.31	123.99	33.83
ETS certificate price	0.95	1.20	2.30	8.29
World certificate price	0.95	1.20	2.30	8.29
Uniform tax	*21.27*	*29.09*	*56.93*	*27.96*

The uniform tax presented in the last line of table 7 allows for an equivalent total CO_2 abatements 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 8 suggest that modeling the use of combustible fuels in commercial buildings with an energy-systems model, as it is 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 (-15%) seems rather limited when compared to the reductions in the residential sector (-56%).

Table 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*	1%	-3%	1%	-3%
incl. CER		*-25%*	*-42%*	*-40%*	*-60%*
- *Households*	*8.4*	5%	5%	5%	5%
- *Transport sectors*	*3.9*	-6%	-20%	-7%	-22%
Residential	*11.3*	-43%	-56%	-57%	-78%
ETS Sectors	*5.4*	-18%	-26%	-20%	-32%
incl. CER		*-23%*	*-35%*	*-30%*	*-48%*
Other sectors	*15.5*	-8%	-16%	-12%	-21%
- *Air transport*	*4.3*	-6%	-18%	-6%	-17%
- *Other*	*11.2*	-8%	-15%	-14%	-23%
Domestic CO_2	*44.6*	-15%	-24%	-21%	-32%
Domestic CO_2 (wo Air transport)	*40.2*	-16%	-25%	-22%	-34%
- *Combustible fuels*	*22.5*	*-26%*	*-36%*	*-36%*	*-51%*
Other GHG	*8.2*	-11%	-10%	-12%	-11%
- CH_4	*4.3*	-26%	-26%	-27%	-27%
- N_20	*3.6*	-26%	-26%	-27%	-26%
- *Fluorinated Gases*	*0.2*	476%	490%	476%	490%
Domestic GHG emissions	*52.8*	-15%	-22%	-19%	-29%
Net GHG emissions	*52.8*	-21%	-32%	-30%	-44%

[a] in $MtCO_2eq$

Both the transport and the ETS sectors can purchase CERs within predefined limits. Table 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 for 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 4 and 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.

Table 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%

5.1.2 Economic and welfare impacts

Table 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]. Furthermore, it presents the impacts of the uniform CO_2 tax that would allow for equivalent CO_2 reductions, while respecting a minimal share of domestic abatement equal to the one achieved in scenario 1. 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 impacts are non-negligible as they are above a half percentage point as of 2013. Despite the limited purchase of permits and positive GTT, the DWL is sufficiently important to affect welfare significantly (-0.56% of HC in 2020).

The numbers in the table 10 also show that if a uniform CO_2 tax is used instead of the combination of instruments, the resulting welfare effects are smaller by a substantial amount. The difference between the two welfare effects can be seen as the 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 and some even benefit from the policies. The most affected sector is the refined petroleum sector, whose demand from households drops by 35% in 2030. Such structural changes are obviously the aim of climate policies. The produc-

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

Table 10: Economic impacts of scenarios 1 and 2 in Switzerland (% of HC)

	Scenario 1		Scenario 2	
	2020	2030	2020	2030
Households' Surplus	-0.56%	-0.49%	-0.75%	-0.66%
GTT	0.16%	0.08%	0.26%	0.21%
Sales of permits	0.00%	-0.01%	-0.01%	-0.08%
Deadweight Loss	-0.72%	-0.55%	-1.00%	-0.79%
in case of uniorm tax				
Households' Surplus	*-0.52%*	*-0.49%*	*-0.62%*	*-0.61%*
GTT	*0.12%*	*0.05%*	*0.17%*	*0.16%*
Sales of permits	*0.00%*	*-0.01%*	*-0.01%*	*-0.08%*
Deadweight Loss	*-0.64%*	*-0.52%*	*-0.78%*	*-0.70%*

tion 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 (61%) is obviously supported by a strong increase of imports (41%). The electricity sector also strongly benefits from the policies and sees its production increase by almost 8% 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 8).

5.1.3 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 5 shows that in the residential sector the combination of the combustible fuel tax and the building improvement program reduce both the diesel and gas usage by respectively 28% and 71% compared to the baseline in 2030. Except in existing multi-family houses where the use of diesel remain predominant, electric heat pumps become the predominant technology for space heating, which triggers the major part of the increase of electricity use (31% compare to the baseline). The instruments also trigger an increase of 13% in the use of insulation and other energy saving technologies.

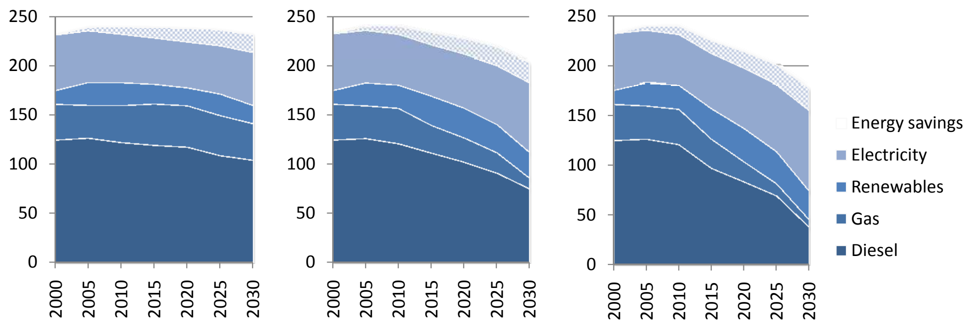

Figure 5: Baseline / Scenario 1 / Scenario 2 Fuel mixes in the residential sector (PJ)

Figure 6 presents the passenger 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 vehicle 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 car.

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 5.

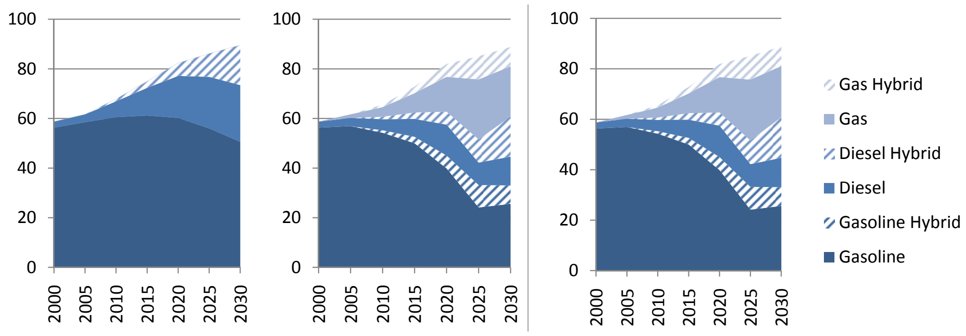

Figure 6: Baseline / Scenario 1 / Scenario 2 Use of personal cars by types (bvkm/a)

5.2.1 Carbon prices and emissions reductions

Tables 11 and 8 present respectively the taxes that allow to achieve 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 253 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 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 32% in 2030. Combustible fuels, ETS sectors excluded, see their share shrink from 43% to 30%.

The tax on combustible fuels seems particularly high when compared to the uniform tax that would allow for an equal domestic and total reduction of emissions and might trigger questions on the social equity aspects of the envisaged policies. Figure 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 60% 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 emis-

Table 11: Swiss environmental taxes and prices of certificates/allowances in scenario 2 (USD_{2008}/tCO_2eq)

	2013	2015	2020	2030
Transport fuels levy	0.21	0.59	2.34	17.69
Combustible fuels tax	54.24	84.83	253.48	191.32
ETS certificate price	1.92	2.95	6.02	30.16
World certificate price	1.92	2.95	5.76	30.16
Uniform tax	*36.92*	*54.43*	*126.36*	*110.77*

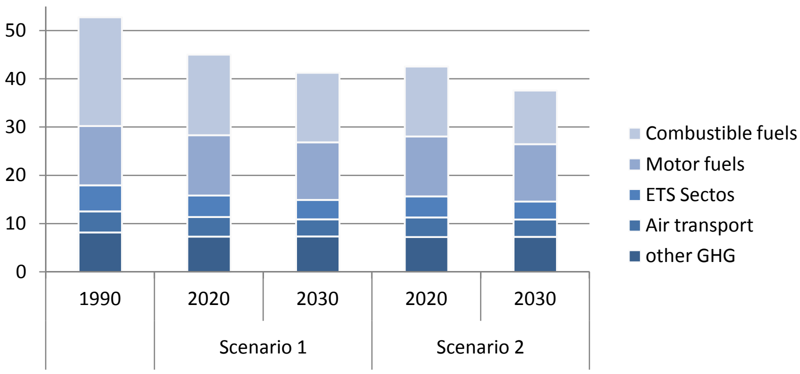

Figure 7: Domestic Swiss GHG emissions ($MtCO_2eq$)

sions reductions, 76% is achieve by the combustible fuels tax and the purchases of CER by the transport sector.

Regarding the purchase of emission certificates by the transport and the ETS sectors, table 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.

5.2.2 Economic and welfare impacts

Table 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 one

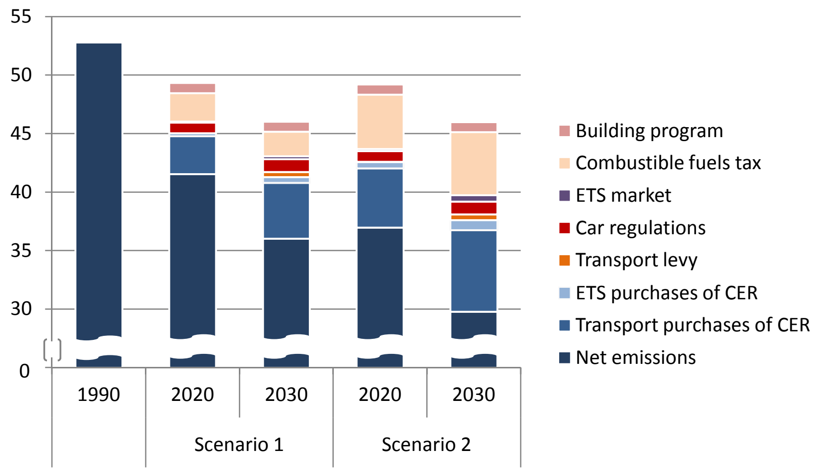

Figure 8: Net Swiss GHG emissions, CER Purchases and abatements by responsible instrument ($MtCO_2eq$)

percent 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 marginal.

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 (-48%). 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 40%. The electricity sector is the major beneficiary in this scenario as it increases its production by 8.7% 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.

5.2.3 The residential and transport sectors

Figure 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 80% and 64% 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 to compensate a large share of the final energy demand and increases the residential use of electricity by 50%. The rest of the final energy is compensated by an increase of 55% in the use of renewables and an additional installation of energy saving technologies (23%).

Figure 6 show that only the car regulation influences the passenger cars fleet composition. Indeed, the limited amount of transport levy does not have further influences. The use of the uniform tax does not further affect the passenger cars fleet and has a very limited impact of other parts of the transport sector, which is very inelastic over the time horizon until 2030.

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. Linking the models allows for the modeling of 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 to analyze 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 half a percent. In the second scenario, the welfare loss would reach 0.75% of HC. 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 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 increased number of gas ICE and hybrid passenger cars. 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 passenger cars fleet composition. The car regulations are responsible for a strong penetration of gasoline and diesel hybrid cars as well as gas hybrid and conventional cars. 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 for 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.

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A Characteristics of the models

Table 12 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 13 presented the values of the elasticity parameters in both production and consumption functions. Tables 14 and 15 show the useful demands in MARKAL-CHRES.

Table 12: Dimensions of the complete and aggregated GEMINI-E3 Model

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

B 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

Table 13: 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 14: 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

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.

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

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

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:

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

Table 15: 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

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:

$$\Phi_{jirCHE} = \begin{bmatrix} 1 & & & & & & & \\ & \ddots & & & & & & \\ & & 1 & & & \mathbf{0} & & \\ & & & \underbrace{1\cdots1}_{12a\cdots12g} & & & & \\ & & & & 1 & & & \\ & & & & & \ddots & & \\ & \mathbf{0} & & & & & 1 & \\ & & & & & & & \underbrace{1\cdots1}_{17a\cdots17e} \\ & & & & & & & & 1 \end{bmatrix} \tag{3}$$

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

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 function:

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

.

Exports are calculated as follows:

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

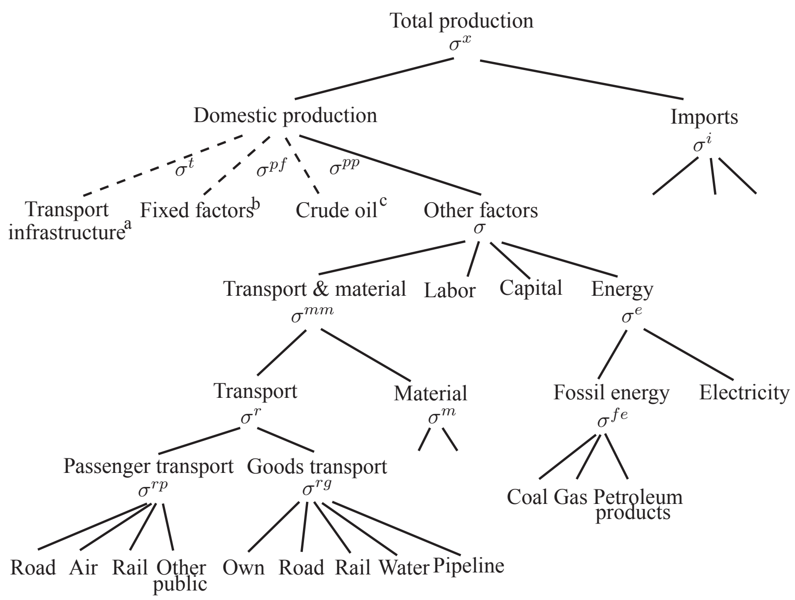
and the price of Swiss exports on the international market are calculated with the following formula:

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

.

B.1 Revised production functions

As explained in chapter 2.1.1, 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 9 presents the Swiss nested CES production function. The σ^x refer to the elasticity parameter of each node (values can be found in table 13 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.



[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 9: Structure of the Swiss nested CES production function

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

$$XDT_{iCHE} = Y_{iCHE} \cdot \lambda^{x}_{iCHE} \cdot \alpha^{x}_{iCHE} \cdot \left[\frac{PY_{iCHE}}{\lambda^{x}_{iCHE} \cdot PDT_{iCHE}} \right]^{\sigma^{x}_{iCHE}}$$
$$, \forall i = 12b, 12c, 12d, 13, 14, 12e, 12f, 12h \quad (8)$$

where the variables and parameters are the same as in equation 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:

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

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:

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

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:

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

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 spited into sectors 12 to 14, whereas for Switzerland we first differentiate between passenger and goods transport using the following CES functions:

$$PATR_{iCHE} = TR_{iCHE} \cdot \lambda^{r}_{iCHE} \cdot \alpha^{r}_{iCHE} \cdot \left[\frac{PTR_{iCHEr}}{\lambda^{r}_{iCHE} \cdot PPATR_{iCHE} \cdot} \right]^{\sigma^{r}_{iCHE}} \tag{12}$$

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

The prices of the various nests are calculated as follows:

$$\begin{aligned} PTR_{iCHE} = \lambda^{r}_{iCHE} \cdot \Big[& \alpha^{r}_{kiCHE} \cdot PPATR^{1-\sigma^{r}_{iCHE}}_{kiCHE} \\ & + (1 - \alpha^{r}_{kiCHE}) \cdot PGOTR^{1-\sigma^{r}_{iCHE}}_{kiCHE} \Big]^{\frac{1}{1-\sigma^{r}_{iCHE}}} \end{aligned} \tag{14}$$

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

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

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

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

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

B.2 Revised final consumption

Figure 10 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.

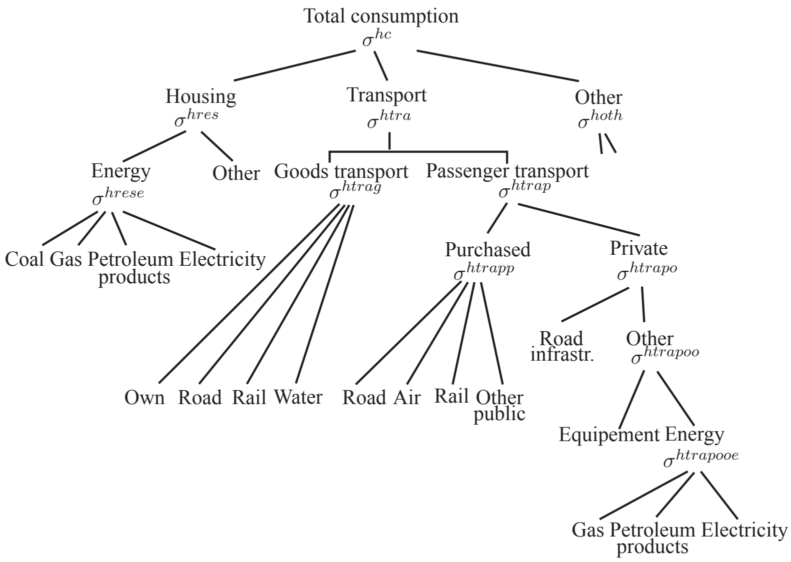


Figure 10: Structure of the households' nested CES utility function

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

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

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

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:

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

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

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.

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

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

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

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

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.

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

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

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

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

$$HC^{tra}_{16,CHE} \cdot \theta^{tra16\,CHE}_{r} = HCTRAPOO_{CHE} \cdot \lambda^{htrapoo}_{CHE} \cdot (\alpha^{htrapoo}_{CHE}) \cdot \left[\frac{PCTRAPOO_{CHE}}{PC_{16\,CHE} \cdot \lambda^{hptrapoo}_{r} \cdot \theta^{tra16\,t}_{CHE}}\right]^{\sigma^{htrapoo}_{CHE}}, \qquad (28)$$

$$HCTRAPOE_{CHE} \cdot \theta^{htrapoo\,t}_{CHE} = HCTRAPOO_{CHE} \cdot \lambda^{htrapoo}_{CHE} \cdot (1-\alpha^{htrapoo}_{CHE}) \cdot \left[\frac{PCTRAPOO_{CHE}}{PCTRAPOE_{CHE} \cdot \lambda^{htrapoo}_{CHE} \cdot \theta^{htrapoe\,t}_{CHE}}\right]^{\sigma^{htrapoo}_{CHE}}, \qquad (29)$$

Moreover, the households transportation consumption of energies ($HC^{tra}_{i\,CHE}$) is calculated as:

$$HC^{tra}_{i\,CHE} = HCTRAPOE_{CHE} \cdot \lambda^{htrapooe}_{CHE} \cdot \alpha^{htrapooe}_{i\,r} \cdot \left[\frac{PCTRAPOE_{r}}{PC_{i\,CHE} \cdot \lambda^{htrapooe}_{CHE}}\right]^{\sigma^{htrapooe}_{CHE}}, \ \forall i = 1, \ldots, 5, \qquad (30)$$

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:

$$HC_{i\,r} = HC^{res}_{i\,r} + HC^{tra}_{i\,r}, \ \forall i = 1, \ldots, 5, \qquad (31)$$

$$HC_{16\,CHE} = HC^{tra}_{16\,r} + HC^{oth}_{16\,r}. \qquad (32)$$

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

C 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 16 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[8].

Table 16: 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

$$GTT = \sum Exp_0 \triangle Pexp - \sum Imp_0 \triangle Pimp$$

[8]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.