Lowering CO_2 emissions in the Swiss transport sector

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Abstract

In Switzerland, transportation represents 41% of CO_2 emissions from energy combustion, a much higher share than in the EU (27%) of the US (31%). Moreover, if total Swiss CO_2 emissions decreased by 11% since 1990, CO_2 emissions from transport increased by 6% over the same period. Our projections (EPFL 2017) show that the contribution of the transport sector would remain constant within a scenario taking into account climate and energy policy measures already implemented or adopted in 2016. In the EU, several initiatives have already pointed out the necessity to limit the use of petroleum products in transportation. The Swedish automaker Volvo plans to stop selling cars with traditional internal combustion engines by 2019; the French government wants to ban sales of gas and diesel vehicles by 2040; Germany plans also to implement significant policies to reduce the use of fossil energy in transportation. In this paper we assess similar targets in the Swiss transport sector. In a first section we will describe the existing situation regarding Swiss CO_2 emissions from the transport sector. In a second section we will describe the existing Swiss measures implemented in this sector and try to evaluate their resulting CO_2 saving since 1990 and up to 2035. The modeling of the transport sector in GEMINI-E3 will be described in section three. In this version of the model, we represented electric cars as well as biofuel as a substitute to fossil fuels. In a fourth section we will present the results of the several simulations that try to encompass the future of the Swiss climate policy with an emphasis on the transport sector. The last section will conclude.

Our simulations show that Switzerland can decarbonize, i.e. lower its energy-related CO_2 emissions to 1.5 ton per inhabitant in 2050, by extending the existing CO_2 levy to all sources and raising it gradually from the current 82 CHF per ton CO_2 to 652 CHF in 2050. This maximum levy would amount to about 1.50 CHF per liter gasoline, so it would double its current price. The burden for energy-intensive firms exposed to international competition could seem too high, in which case the existing ETS could be maintained. These firms would then pay a price per certificate of 193 CHF per ton CO_2, less than in the reference scenario (252 CHF) because their emissions would be reduced somewhat by lower production and less oil refining. They would also mitigate less, which implies more abatement with a higher CO_2 levy for the other sectors and consumers (738 CHF). If the transport sector also benefits from a preferential treatment and only pays one fourth of the CO_2 levy on thermal fuels, then we estimate levies of 1676 CHF for the latter and 419 CHF for the former. Doubling the levy on thermal fuels is needed to compensate for emissions in transportation that are 57% higher than in the uniform CO_2 levy scenario (with ETS).

These decarbonization scenarios imply that total consumption in 2050 is lower than in the baseline, by between 0.74% (in uniform tax scenario) and 1.01% (in differentiated tax with ETS scenario). These welfare costs are about 80% larger in similar scenarios that aim at reducing energy-related CO_2 emissions to 1 ton per inhabitant in 2050. The advantage of the uniform tax scenario compared to the scenarios with preferential regimes is somewhat greater in this more ambitious program. In addition, the preferential regimes concentrate the costs on non-ETS sectors and thermal fuels. The ETS regime, without tightening of its cap relative to the baseline, leads to additional welfare costs of 0.26% of household consumption. When transport fuels pay only one fourth of the CO_2 levy on thermal fuels, this levy must rise above 3000 CHF and welfare costs increase by 0.28% of household consumption. The often mentioned interaction effect with high pre-existing taxes on transport fuels is not an excuse for its preferential treatment under carbon taxation when the carbon tax that must be imposed on the non-preferred sectors is so high that it exceeds the sum of those pre-existing taxes and the preferential carbon tax on transport fuels.

The needed carbon prices and the welfare costs would be lower with faster innovation than in our conservative assumptions. Indeed, our analysis does not consider disruptive technology developments, only a gradual penetration of electric vehicles and biofuels.

Keywords: Keywords: climate policy, transport decarbonization, computable general equilibrium model, Switzerland

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1. Introduction

News concerning the demise of the internal combustion engine are coming in nearly every day. France's minister for the ecological transition announced plans to forbid the sale of petrol and diesel cars in 2040 and to implement a feebate system designed to remove them gradually from the streets. In Norway and Germany, this could happen as early as 2025, whereas Dutch plans mention 2030 as a target. Amsterdam just announced that it would ban these cars from its center in 2025 already, in order to hold down air pollution. Other cities have similar plans or they implement selective road tolls that discourage polluting cars. The European Commission proposes targets for average CO_2 emissions for new passenger cars and vans for 2030 that are 30% below those of 2021, and it takes action for the modernization of European mobility and transport (European Commission, 2016). Many other countries, such as China, announce ambitious quotas for electric vehicles.

Even if these are mostly announcements, they put strong pressure on carmakers to reform their vehicle production. Thus, Volvo plans to produce only electric or hybrid cars from 2019 onwards. The replacement of fossil fuel cars by electric vehicles will still require major technical improvements in batteries and their recycling and vast investments in the production and maintenance of cars, and in the generation and distribution of electricity (Kannan and Hirschberg, 2016). In parallel, innovation in driving technologies, in car ownership and sharing, and in the alternatives of public transportation and soft mobility are profoundly reshaping the transportation sector, with a strong potential for lowering its CO_2 emissions.

Compared to these developments, the Swiss plans regarding the CO_2 emissions of the transport sector look very timid, indeed. They do not deviate from a tradition of leniency towards the automobile sector, which could essentially set itself its targets for fuel efficiency improvement and CO_2 emissions reduction and compensation. In this paper, we show how transport-related CO_2 emissions evolved in the recent past, we estimate their evolution under the existing set of measures implemented or planned with a view to reducing them, and we simulate ambitious targets, compatible with deep decarbonization by 2050. The context is given by the deep decarbonization simulations performed within the SEMP study (Landis et al., 2018).

The paper is organized as follows. In section 2, we describe the existing situation regarding Swiss CO_2 emissions from the transport sector and in section 3 we describe Swiss policies already implemented in this sector and evaluate the resulting CO_2 savings since 1990. The modeling of the transport sector in GEMINI-E3 is described in section 4. In this version of the model, we represent electric cars as well as biofuels as substitutes to fossil fuels. In section 5, we present the results of the SEMP simulations with an emphasis on the transport sector. The last section concludes.

2. Contribution of transport to CO_2 emissions

In 2015, the transport sector emitted 15.2 Mt CO_2, which represents 42% of Switzerland's CO_2 emissions from energy combustion. The comparable shares are 27.5% as an EU average and 33.5% in the USA. From 1990 to 2015, the CO_2 emitted by the Swiss transport sector increased by 5.7% while the emissions from the other sectors decreased by 20% (see Figure 2). The majority of the transport CO_2 (98%) is emitted on the roads, where private passenger vehicles account for two thirds of these emissions.

As pointed out by Alberini et al. (2016), the CO_2 emissions of new Swiss passenger cars are among the highest in Europe. In 2015, they emitted on average 135 g of CO_2 per kilometer, compared to 111 g in France, 127 g in Germany, 121 g in United Kingdom and 120 g as an EU average (The International Council on Clean Transportation, 2016). The main explanation is the high average purchasing power of Swiss households, as can be illustrated by the highest percentage of 4-wheel drive registrations in Europe, equal to 40% in 2015 compared to an average of 13% in the European Union (The International Council on Clean Transportation, 2016).

The disappointing contribution of transportation to Swiss CO_2 emissions reductions is also due to a context of relatively strong demographic and economic growth. Between 1990 and 2015, the population grew by 23%, GDP by 46%, the number of cars by 49%, and the number of vehicle-kilometers by 33% (all data Federal Office of Statistics). Transportation activity is officially predicted to increase further by 25% (passengers) and 37% (freight) relative to 2010 at the horizon of 2040 in the reference scenario (ARE, 2016). Modal shares are not expected to change much, so the expected increase of road traffic is of similar magnitude. Therefore, strong policy measures are needed to curb total CO_2 emissions from the transport sector.

3. Swiss climate policies in the transport sector

When debating the first CO_2 Act in the early 2000, the federal Parliament agreed on a 10% reduction target for the period 2008-2012 compared to 1990, a target compatible with Switzerland's commitment under the Kyoto Protocol. The Parliament decided to split this target into a 15% reduction target for heating and process fuels (thermal fuels) and an 8% reduction target for motor fuels (transport fuels). The motive for two separate targets was that the MPs were quite aware that it would be difficult to reduce emissions in transportation and they did not want the other sectors to be forced to make extra efforts in compensation for that. This split opened the way for a differentiated CO_2 levy for thermal and transport fuels. While the first was introduced in 2008, the latter was replaced in the last minute by a voluntary contribution of the transport fuels sector of 1.5 Swiss cents per liter gasoline and diesel into a fund managed by a foundation created by this same sector, the Climate Cent Foundation. From 2008 to 2012, this organization contributed to emission mitigation projects in Switzerland and, predominantly, in the rest of the world. This is how it could compensate the 13% increase in CO_2 emissions from transport fuels relative to 1990.

The revised CO_2 Act for the period 2013-2020 set as its main target a 20% reduction of total greenhouse gas emissions by 2020 relative to 1990. Intermediate targets were set for 2015 and they were not updated. The target for transport fuels was that their CO_2 emissions should be down to their level of 1990. They were still 5.7% higher, but at least they are decreasing. The climate cent was replaced by an explicit compensation requirement: 2% of the CO_2 implicit in transport fuels imported or refined in 2014 and 2015 was to be compensated by additional domestic greenhouse gas mitigation measures. The compensation ratio is gradually increased, up to 10% in 2020. In addition, the voluntary fuel standards in place since 1996 were replaced by a somewhat more compelling system targeting a fleet average for new cars of 130 g CO_2 per kilometer from 2015 on. The statistical average of registrations was 135 g, down from 151 g in 2012. It was estimated that 85% of this energy efficiency improvement is due to the general trend and to measures taken abroad and only 15% can be attributed to Swiss measures such as the energy efficiency label (INFRAS, 2017). The emissions limit was revised in the context of the new Energy Act: it was lowered to 95 g CO_2 per kilometer from 2023 on.

Measures taken outside of climate policy also affect CO_2 emissions from transportation, for instance the promotion of public transportation and the distance-related heavy vehicle charge. The latter was introduced in 2001 on passenger and freight transport vehicles of more than 3.5 tons gross weight. It increases with vehicle-specific maximum authorized gross weight but decreases for higher EURO classes. It thus encourages the more efficient use of vehicles, the choice of less polluting vehicles and the transfer of freight and vehicles onto the rails. The CO_2 savings induced by this measure were estimated at 3 million tons for the period 2001-2030 (Betschart et al., 2016).

4. The GEMINI-E3 model

4.1. Overview of the model

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium (CGE) model comparable to other CGE models (EPPA, OECD-Env-Linkage, etc) built and implemented by other modeling teams and institutions, and sharing the same long experience in the design of this class of economic models. The standard model is based on the assumption of total flexibility in all markets, both macroeconomic markets, such as the capital and international trade markets (with the associated prices being the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production, etc.).

The current version is built on the Swiss input-output table 2008 (Nathani et al., 2011) and the GTAP database 8 (Badri Narayanan et al., 2012) for the other countries. The industrial classification used in this study comprises 11 sectors and is presented in Table 1. The model describes five energy goods and

Table 1: Industrial and regional classifications

Sectors/goods	Countries/regions
1 Coal	CHE Switzerland
2 Crude oil	EUR European Union
3 Natural gas	USA United States of America
4 Petroleum products	BIC Brazil, Russia, India and China
5 Electricity	ROW Rest of the world
6 Agriculture	
7 Energy intensive industries (EII)	
8 Other goods and services	
9 Land transport	
10 Water transport	
11 Air transport	

sectors: 1) coal; 2) oil; 3) natural gas; 4) petroleum products and 5) electricity. Regarding spatial decomposition, we use an aggregated version of GEMINI-E3 that describes only five country/regions: 1) Switzerland; 2) European Union; 3) United States of America; 4) BRIC (Brazil, Russia, India, and China); and 5) the rest of the world.

4.2. The transport sector

By definition, macroeconomic models such as CGE models encompass the whole economy and cannot address with great detail each economic sector. Another constraint is the statistical database of these models, based mainly on a social accounting matrix where the technological representation is weak and doesn't capture correctly the existing and future technological options. This is of course the case for the transport sector and especially the passenger vehicle transport. Indeed, in a standard CGE models road transport is mainly based on petroleum fuel consumption and doesn't integrate alternative fuel vehicle technologies that are likely to change its technological paradigm in the next decades. In order to better capture the specificities of the transport sector in a CGE model, several approaches have been proposed and implemented in the literature. The first strategy is to link the CGE with a bottom-up model that integrates a technology rich description of the energy system. An example for transport in Switzerland is the work done by Sceia et al. (2012) with the GEMINI-E3 model. It linked the GEMINI-E3 model with the Swiss MARKAL model developed at the Paul Scherrer Institute. The transport sector is therefore represented by the submodule MARKAL-CHTRA that allows to simulate the existing Swiss technical regulations for cars.

Another approach is to implement directly into the model a technology-rich representation that addresses the main features of transport demand such as fleet turnover, alternative fuel vehicle choices, etc. This is the method tested in the MIT EPPA model and implemented by Karplus et al. (2013).

The approach developed in this article follows the second approach but with a less detailed representation of the transport sector. The objective is to describe the main technological options that could be used in road vehicles within the next decades.

In GEMINI-E3, *for-hire transportation services* are represented through three sectors:

1. land transport that includes railways (passenger and freight), road (passenger and freight) and pipelines;
2. water transport, which is mainly fluvial in Switzerland;
3. air transport (freight and passenger).

In the national accounts, *in-house transportation* (also called own transport) by firms and by households are not produced by the above three sectors. They are accounted as intermediate consumptions (for firms) and final consumption (for households) in the input-output table. For example, transport done by households with a car is represented as a final consumption of petroleum products and vehicles (representing the ownership of the car).

Figure 1 shows how household consumption is represented in this GEMINI-E3 version and in particular what assumptions are retained concerning transport demand by households. The latter is represented at the top of the nested constant elasticity of substitution functions (CES) structure, together with housing demand and other consumptions. Then, we distinguish long distance travel, which is supposedly done by air. The other trips (medium and short distances) can be done with public transportation (i.e. railways, bus and boat) or with personal vehicles (mainly cars). The model distinguishes three types of personal vehicles depending on the fuel used. Electric vehicles (EV), which are mainly dedicated to short or medium distancse[1], and two other types using the same motorisation (i.e. internal combustion), except that one uses petroleum products and the other biofuels.

4.3. Other important features

GEMINI-E3 allows the use of carbon capture and storage (CCS) technology in electricity generation with natural gas. This technology is implemented after 2030 when the price of carbon exceeds the cost of CCS. IEA in Finkenrath (2011) evaluates the cost of CO_2 capture on average at 80 \$ per ton of CO_2 for natural gas-fired power plants. The costs per ton of transported CO_2 vary from 2 \$ to 6 \$ for 2 Mt transported over 100 km according to another IEA publication (International Energy Agency, 2008). The same publication estimates the cost of CO_2 storage in deep saline aquifers for Europe from 1.90 \$ per ton of CO_2 to 6.20 \$. Therefore, in this paper we suppose that CCS will begin to be implemented in Switzerland at a cost of 100 \$ per ton of CO_2. The CO_2 sequestration potential is significant in Switzerland, at around 2680 Mt (Diamond et al., 2010).

When an emissions trading system (ETS) is implemented, we consider that the following sectors participate in this market: the refined petroleum sector (i.e. mainly refineries), the energy intensive industries and the power generation sector. For this latter sector and according to the second CO_2 Act, we assume

[1] This will gradually change as the range of EV increases.

Figure 1: Nested CES structure of household consumption

that power plants using natural gas (i.e. gas-fired combined-cycle power plants (GCCPP)) are required to compensate their emissions, with a minimum share of 50% domestic compensation. The rest can be compensated internationally. Therefore, when a scenario assumes that an ETS is implemented, emissions from GCCPP are not included in this market. We fix the price of foreign certificates (linked to international compensation) at 10 CHF/t CO_2 following Vielle and Thalmann (2017).

5. Simulations results

In this section, we detail the results of the reference scenario, and then focus on the SEMP scenarios.

5.1. The reference scenario

Our reference scenario is closely calibrated to the harmonized assumptions retained in the SEMP study (Landis et al., 2018). Swiss population and GDP growth, energy prices and Swiss HDD follow these common assumptions. For the other regions, we retain assumptions that are close to those of the World Energy Outlook 2015 (International Energy Agency, 2015).

In the reference scenario, the CO_2 levy (applied only on thermal fuel) reaches 120 CHF per ton of CO_2 in 2018 and remains stable thereafter. The ETS price increases over the simulation period in order to satisfy the annual CO_2 ETS emissions reduction of 1.74% between 2013 and 2050 (i.e. a 48% reduction with respect to 2013 level). The ETS price computed by GEMINI-E3 is equal to 68 in 2020 and rises to 252 CHF in 2050 (see Table 2).

The resulting CO_2 emissions are shown in Figure 2. Our scenario is consistent over the period 2015-2035 with the scenario WEM ("with existing measures") computed with GEMINI-E3 for the Federal Office for the Environment (Vielle and Thalmann, 2017), for which we assumed that Swiss climate and energy policy measures existing or adopted since 2016 are implemented. On the period 2015-2050, the CO_2 emissions decrease by 0.9% per year and reach 26.5 Mt CO_2 in 2050 representing 2.6 tons of CO_2 per inhabitant. The main contributor to this decrease is the residential sector with an annual percentage decrease of 2.4%, followed by the road transport sector with an annual decrease of 0.9%. In the other sectors, CO_2 emissions decrease by only 0.2% per year.

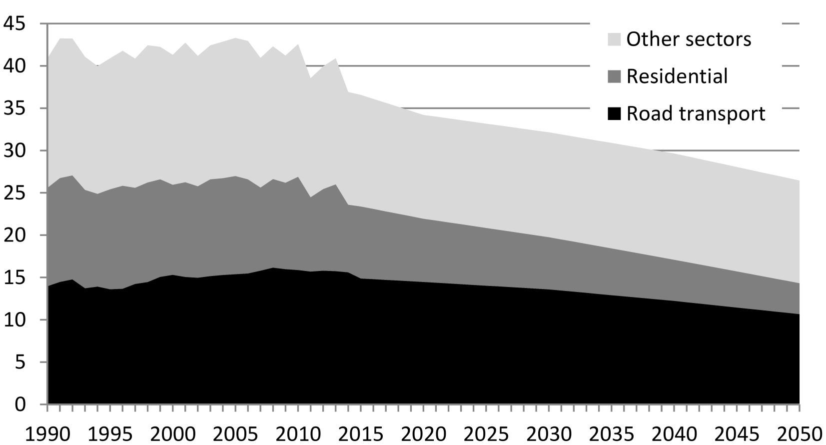

Figure 2: CO_2 emissions from energy combustion (1A) in the reference scenario in Mt CO_2 (1990-2015: historical values)

In the transport sector, CO_2 reductions are achieved through three channels:

- a modal shift in favor of railways transport (consistent with the assumptions made in the Swiss energy perspectives (Prognos, 2012));
- the improvement of the energy efficiency of vehicles;

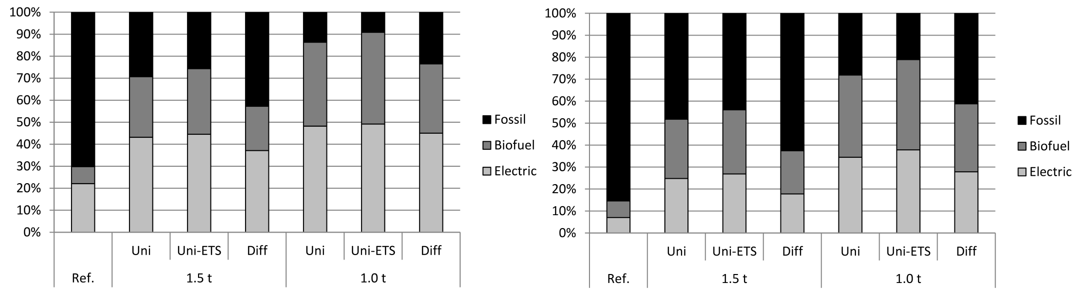

Figure 3: Fuel mix in percentage in 2050 - Cars (left) and Other vehicles (right)

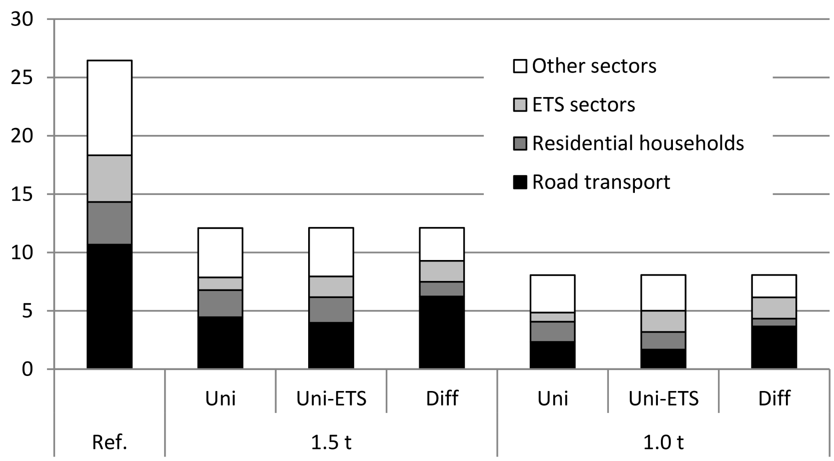

Figure 4: CO_2 emissions in Mt CO_2 by sector in 2050

- and the penetration of biofuel and electric vehicles in road transport.

Figure 3 describes the fuels used for road transport. In 2050, fossil fuels still dominate for cars and other vehicles (light and heavy duty vehicles, coaches, buses) in the reference scenario. However, electricity penetrates passenger cars; its share equals 22% in 2050; for other vehicles the share of electricity equals 7%. Regarding biofuels, their contribution reaches 8% for both types of vehicles. These evolutions were calibrated on exogenous assumptions derived by INFRAS (a Swiss research and consulting company) from a bottom-up analysis.

5.2. The 1.5 t CO_2-eq per capita scenarios

In this scenario we assume that Switzerland implements a climate policy with the goal to achieve in 2050 a level of GHG emissions per capita equal to 1.5 ton of CO_2-eq. Translated in CO_2 emissions from energy combustion it

Table 2: CO_2 prices and welfare cost in 2050

		1.5 t			1.0 t		
	Ref.	Uni	Uni-ETS	Diff-ETS	Uni	Uni-ETS	Diff-ETS
Average CO_2 price	82	652	637	746	1089	1010	1255
-ETS sector	252	652	193	196	1089	174	176
-transport fuel	0	652	738	419	1089	1331	794
-thermal fuel	121	652	738	1676	1089	1331	3175
Cost (in% of household cons.)		0.74%	0.85%	1.01%	1.33%	1.60%	1.88%

represents a target of 1.2 ton of CO_2 per inhabitant, i.e. an abatement of 54% with respect to the emissions of the reference scenario, or a 67% reduction with respect to the 2015 level. Following the guidelines of the SEMP exercise, we implement this target in three different ways:

- the first scenario (called "Uni") assumes that the existing carbon pricing, which combines a CO_2 levy and an ETS price, is replaced by a uniform CO_2 levy on all fossil energy consumptions;
- in the second scenario (called "Uni-ETS"), the ETS market is maintained with the same caps as in the reference scenario (-1.74% annually), but the CO_2 levy is extended to all other fossil energy consumptions (i.e. transport fuel);
- finally, the third option (called "Diff-ETS") assumes that the CO_2 levy introduced on the energy used for transportation purposes is equal to a quarter of the CO_2 levy on thermal fuels. The ETS market is maintained with the same caps as in the reference scenario.

We assume that the budget of the Swiss government remains unchanged across the scenarios for any given year. This is achieved by returning to the households the difference between government revenues in the policy scenarios and the revenues in the reference scenario. This recycling is through lump-sum transfers.

Figure 4 shows the resulting carbon emissions per sector, and Table 2 indicates the associated CO_2 prices and welfare costs expressed in % of household consumption for the year 2050. The uniform price scenario represents the most efficient policy option with a carbon price equal to 652 CHF and a welfare cost evaluated to 0.74% of household consumption. A more realistic scenario that combines an ETS market with a uniform price for thermal and transport fuels increases the welfare cost by 15% whereas the differentiated price scenarios induces an incremental cost equal by 36%. The hierarchy between the scenarios is consistent with the results presented by Landis et al. (2017) in a similar context for Switzerland.

By definition, the emissions from the ETS sectors remain the same as the one computed in the reference scenario when an ETS is implemented (see Figure 4). But the ETS price decreases significantly with respect to the price computed in the reference scenario (i.e. more than 20%). Indeed, the decrease in oil products consumption induces additional CO_2 emissions abatement in the refined petroleum sectors following the loss of production by refineries. When a uniform carbon price is implemented (scenario 1), the additional abatement of CO_2 emissions by ETS sectors is equal to 36%.

In the road transport sector, the scenarios that assume a uniform carbon tax on transport and thermal uses induce a significant penetration of biofuels as well as EV (see Figure 3). A tax differentiated scenario limits, of course, this penetration and the contribution of road transport to CO_2 abatement. In the third scenario, the CO_2 emissions from this sector are 40% higher than in the uniform carbon price scenario and 57% higher than in the “Uni-ETS” scenario. This requires, of course, additional abatement in the other sectors, which is obtained with a carbon price on thermal fuels multiplied by more than a factor 2. This result is comparable with that obtained by Imhof (2012), where the full exemption of transport fuels also doubles the CO_2 price on stationary fuels. It is in contrast, however, with results of Abrell (2010), who found that a preferential treatment for the transport sector lowered the costs of a climate target due to pre-existing taxes on transport fuels (tax interaction effect). We do not find the same result for the following reason. The pre-existing taxes on transport fuels amount to about 85 CH cents per liter or 360 CHF per ton CO_2. In scenario 3 with the carbon tax on transport fuels only one fourth of the carbon tax on thermal fuels, the CO_2 levy added on the price of transport fuels is 419 CHF per ton. Adding this to the pre-existing 360 CHF makes for a total tax burden on transport fuels that is still less than half the burden that must be imposed on thermal fuels to meet the emissions target.

5.3. The 1.0 t CO_2-eq per capita scenarios

These scenarios aim at stronger abatement, so that CO_2 equivalent emissions do not exceed 1 ton per capita in 2050. The needed abatement is 70% with respect to the emissions of the reference scenario or 78% with respect to the 2015 level. The same three policy scenarios (“Uni”, “Uni-ETS” and “Diff-ETS”) are simulated.

Not surprisingly, stronger abatement requires an increase of the CO_2 prices and leads to higher welfare costs. The main findings of the previous scenarios remain, nevertheless, unchanged. The most efficient scenario is still the uniform case, but the cost differences with the other scenarios are increasing with the degree of abatement.

In the “Uni-ETS” and “Diff-ETS” scenarios, the sectors participating in the ETS are protected against the CO_2 price increase, as they are not committed to additional abatement. This situation is unfair and probably politically not realistic, as the burden is shifted on the other sectors. In these two scenarios, their emissions represent 28% of CO_2 emissions in 2050, compared to 8% and 18% in the reference scenario and the ETS scenarios for the 1.5 ton CO_2-eq goal. These sectors always complained that energy costs are key for their international competitiveness, to which they are more exposed than the other sectors. Despite this, protecting them through the ETS market results in an estimated overall welfare cost of 0.26% of household consumption, which is significant.

The conservation of a lower carbon tax for transport fuels raises the required CO_2 tax on thermal fuels to 3175 CHF and induces similar welfare costs of 0.28% of household consumption in 2050.

6. Conclusion

Our simulations show that Switzerland can decarbonize, i.e. lower its energy-related CO_2 emissions to 1.5 ton per inhabitant in 2050, by extending the existing CO_2 levy to all sources and raising it gradually from the current 82 CHF per ton CO_2 to 652 CHF in 2050. This maximum levy would amount to about 1.50 CHF per liter gasoline, so it would double its current price. The burden for energy-intensive firms exposed to international competition could seem too high, in which case the existing ETS could be maintained. These firms would then pay a price per certificate of 193 CHF per ton CO_2, less than in the reference scenario (252 CHF) because their emissions would be reduced somewhat by lower production and less oil refining. They would also mitigate less, which implies more abatement with a higher CO_2 levy for the other sectors and consumers (738 CHF). If the transport sector also benefits from a preferential treatment and only pays one fourth of the CO_2 levy on thermal fuels, then we estimate levies of 1676 CHF for the latter and 419 CHF for the former. Doubling the levy on thermal fuels is needed to compensate for emissions in transportation that are 57% higher than in the uniform CO_2 levy scenario (with ETS).

These decarbonization scenarios imply that total consumption in 2050 is lower than in the baseline, by between 0.74% (in uniform tax scenario) and 1.01% (in differentiated tax with ETS scenario). These welfare costs are about 80% larger in similar scenarios that aim at reducing energy-related CO_2 emissions to 1 ton per inhabitant in 2050. The advantage of the uniform tax scenario compared to the scenarios with preferential regimes is somewhat greater in this more ambitious program. In addition, the preferential regimes concentrate the costs on non-ETS sectors and thermal fuels. The ETS regime, without tightening of its cap relative to the baseline, leads to additional welfare costs of 0.26% of household consumption. When transport fuels pay only one fourth of the CO_2 levy on thermal fuels, this levy must rise above 3000 CHF and welfare costs increase by 0.28% of household consumption. The often mentioned interaction effect with high pre-existing taxes on transport fuels is not an excuse for its preferential treatment under carbon taxation when the carbon tax that must be imposed on the non-preferred sectors is so high that it exceeds the sum of those pre-existing taxes and the preferential carbon tax on transport fuels.

The needed carbon prices and the welfare costs would be lower with faster innovation than in our conservative assumptions. Indeed, our analysis does not consider disruptive technology developments, only a gradual penetration of electric vehicles and biofuels.

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