Thalmann and Vielle *Swiss Journal of Economics and Statistics* (2019) 155:10
https://doi.org/10.1186/s41937-019-0037-3

Swiss Journal of
Economics and Statistics

ORIGINAL ARTICLE Open Access

Lowering CO_2 emissions in the Swiss transport sector

Philippe Thalmann and Marc Vielle*

Abstract

In Switzerland, transportation represents 41% of CO_2 emissions from energy combustion (2016), a much higher share than in the European Union (EU) (28%) or even the USA (34%). While total Swiss CO_2 emissions decreased by 10% between 1990 and 2016, CO_2 emissions from transport increased by 4.5% over the same period (all data from UNFCCC database). Our projections (Vielle and Thalmann, Updated emissions scenarios without measures, 1990-2025, Tech. rep., 2017) show that the contribution of the transport sector would remain constant in a scenario taking into account climate and energy policy measures already implemented or adopted in 2016. In the EU, several initiatives have already been introduced to limit the use of petroleum products in transportation. This paper presents deep decarbonization pathways for Switzerland that demand a strong contribution from the transport sector. We find that a preferential treatment of transportation fuels raises the welfare cost of decarbonization by about 18% relative to a uniform tax on all fossil fuels. This is of similar magnitude as the preferential treatment of large CO_2 emitters through an emissions trading system. We also find that the preferential treatment leads to a share of fossil fuels in total energy for road transportation in 2050 which is approximately twice as high as in the uniform treatment.

Keywords: Climate policy, Transport decarbonization, Computable general equilibrium model, Switzerland

JEL Classification: C63, Q41, Q54

1 Introduction

News stories concerning the imminent demise of the internal combustion engine currently seem to appear on an almost daily basis. France's Minister for the Ecology announced plans to ban the sale of petrol and diesel cars by 2040 and to implement a feebate system designed to remove such vehicles gradually from the streets. In Norway and Germany, similar schemes could be implemented as early as 2025, while the Netherlands has a target of the year 2030. Amsterdam has recently announced that cars will be banned from the city centre by 2025, in order to reduce air pollution levels. Other cities have similar plans or plan to implement selective road tolls that will 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, as part of a broader programme of modernization for European transport (European Commission 2016b). Many other countries, such as China, have also announced ambitious quotas for electric vehicles.

Even if these are so far only announcements, they place strong pressure on carmakers to reform their vehicle production. Thus, Volvo announces that by 2025 half of the cars it produces and sells will be electric. 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 is profoundly reshaping the transportation sector, with strong potential for lowering its CO_2 emissions.

Compared to these developments, Swiss plans regarding the CO_2 emissions in 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 emission reduction and compensation. In this paper, we show how transport-related CO_2 emissions evolved

*Correspondence: marc.vielle@epfl.ch
LEURE, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

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. In particular, we estimate the welfare cost of preferential treatment granted to the transport sector and compare it to the welfare cost of another form of preferential treatment: the emissions trading system (ETS) for large emitters. The context is given by the deep decarbonization simulations performed in the context of the Swiss Energy Modelling Platform (SEMP) (Landis et al. 2018).

The paper is organized as follows: In Section 2, we review the existing literature on the decarbonization of the transport sector. In Section 3, we detail the existing situation regarding Swiss CO_2 emissions from the transport sector, describe Swiss policies already implemented in this sector and evaluate the resulting CO_2 savings since 1990. The modelling 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 our simulations with an emphasis on the transport sector. The last section provides a conclusion.

2 Literature review

It is interesting to focus on the transportation sector, not only because it accounts for a large share of CO_2 emissions of many countries[1], but also because it seems politically more difficult to bring it to reduce its emissions than other sectors. This is clearly evidenced in Switzerland, which has been levying a CO_2 tax since 2008, which has been raised gradually to 96 CHF (or USD)/t CO_2 in 2018, but still exempts transport fuels. However, deep decarbonization is not possible without involving the transport sector.

The global transport sector's potential for emission reduction was examined by the International Energy Agency (2009), which concluded that its CO_2 emissions worldwide could be reduced by 40% in 2050 relative to 2005, despite economic and demographic growth, with measures costing not more than USD 200/t. These measures involve the widespread adoption of new vehicle technologies and fuels, along with some shifting in passenger and freight transport to more efficient modes, and some acceptable reduction in mobility. Similarly, Prognos (2012) proposes decarbonization scenarios, including the transport sector, which are still the reference for Swiss energy policy. The most ambitious scenario has the final energy use for transportation reduced by 54% in 2050 relative to 2010, despite much higher levels of service (+ 23% for personal mobility, + 48% for goods). In another scenario, CO_2 emissions from transport fuels may decrease by over 80% thanks to electrification of passenger transport and biofuels in goods transportation.

These scenarios are constructed bottom up: the transport sector is divided into types of transport services and types; forecasts for external determinants such as population and economic growth, living standards and land use are used to extrapolate the demand for transport services; assumptions about sectoral policies, technical progress, modal shifts and other substitutions are used to fine tune the scenarios for vehicle fleets and usages and the energy quantities and mixes they will consume. The vehicle fleets are generally represented in cohorts, with replacement rates that can change. In these bottom-up approaches, the transport sector is influenced by macroeconomic conditions, but it does not reflect back on the macro-economy. It therefore makes no difference for the production costs of firms or the budgets of households, and hence their demands for transportation services, whether the transport sector evolves smoothly along its business-as-usual path or whether it is forced to change. While this might be perfectly fine for small changes, relatively rapid deep decarbonization of the transport sector is a change that could raise transport costs to a level which would feed back significantly to the rest of the economy.

Computable general equilibrium (CGE) models are one approach to modelling the reciprocal interactions between the transport sector and the rest of the economy. A further advantage of the CGE models is that they allow for the computation of economy-wide costs and welfare effects. In order to keep the interactions tractable, they tend to represent the transport sector with less detail than the bottom-up models. This is the route followed in this paper. A solution to this limitation is to couple a detailed bottom-up model of the transport sector with a CGE model. This is the approach followed by Schäfer and Jacoby (2005), Schäfer and Jacoby (2006), Sceia et al. (2012) and Karkatsoulis et al. (2017) for simulating decarbonization pathways in transportation. The three modelling approaches are illustrated by the various contributions to the special section of *Transportation Research Part D: Transport and Environment*, volume 55, on model-based long-term transport scenarios, or in the comparison of transport decarbonization modelling by Pietzcker et al. (2014).

This paper uses a CGE model to simulate the decarbonization of the complete Swiss economy, with and without discriminatory treatment of transport fuels. This approach is suitable for a low-cost assessment of the contribution of the transportation sector to the general decarbonization effort, which emphasizes the interactions between this sector and the other sectors of the

---

[1] For the sum of all Annex-I countries, transportation accounted for 21% of total greenhouse gas emissions in 2016 (calculated from greenhouse gas inventory database of UNFCCC).

economy rather than the fine structural shifts within the transport sector. It is the approach used by Berg (2007) to compare variants of CO_2 taxation applied to transportation in Sweden or by Abrell (2010) to simulate market-based instruments designed to reduce CO_2 emissions of transportation in Europe. For a comprehensive review of CGE models applied to transport issues, see Robson et al. (2018).

3 Swiss transport and CO_2 emissions

3.1 Contribution of transport to CO_2 emissions

In 2016, the transport sector emitted 15 Mt CO_2, which represents 41% of Switzerland's CO_2 emissions from energy combustion. The comparable shares are 28% as a European Union (EU) average and 34% in the USA[2]. From 1990 to 2016, the CO_2 emitted by the Swiss transport sector increased by 4.5% while the CO_2 emissions from energy combustion by the other sectors decreased by 15% (ibid, see Fig. 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 kilometre, compared to 111 g in France, 127 g in Germany, 121 g in the UK 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 four-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-kilometres by 33% (all data Federal Office of Statistics). Transportation activity is officially projected 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 significantly, so the expected increase of road activity is of similar magnitude. Therefore, strong policy measures are needed to curb total CO_2 emissions from the transport sector.

3.2 Swiss climate policies in the transport sector

When debating the first CO_2 Act in 1999, 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 members of the Parliament 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 at the last minute by a voluntary contribution of the transport fuel sector of 1.5 Swiss cents per litre of 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 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 6.3% higher in 2015 (Federal Office for the Environment data with definition of CO_2 Act), 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 towards 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 kilometre from 2015 on. The statistical average of registrations was 134 g, down from 151 g in 2012 (EBP 2017). It was estimated that 85% of this energy efficiency improvement is due to autonomous technical progress 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 kilometre 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 t 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

---

[2] Calculated from greenhouse gas inventory database of UNFCCC.

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).

The updating of the CO_2 Act for 2021–2030 is underway in the Parliament at the time of writing (October 2018). The government's draft has set a 30% reduction target for all greenhouse gases for 2030 relative to 1990. There is no specific target for motor fuels in the draft CO_2 Act, but it sets minimum shares of emissions related to these fuels that must be compensated through other measures or avoided with renewable fuels. The overall target reduction is compatible with the Nationally Determined Contribution submitted by Switzerland to COP21, which also mentions a long-term indicative goal to reduce emissions by 70 to 85% by 2050 relative to 1990. These pledges place Switzerland in the middle field of the pledges made by industrialized countries (Vöhringer et al. 2016). This paper simulates pathways for the long-term goal.

4 The GEMINI-E3 model

4.1 Overview of the model

GEMINI-E3 is a multi-country, multi-sector, recursive CGE model comparable to other CGE models (EPPA, OECD-Env-Linkage, etc.) built and implemented by other modelling 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 (Aguiar et al. 2016) 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 sectors: (1) coal, (2) crude 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) USA, (4) BRIC (Brazil, Russia, India and China) and (5) the rest of the world.

Production functions and preferences are represented through nested constant elasticity of substitution (CES) functions (see for instance in Fig. 1 the nested CES structure of household consumption). The model uses elasticities of substitution taken from the literature and approximate estimates. The representative household maximizes its utility when allocating its income (equal to labour and capital remuneration plus net transfers from the government) over final goods. Its labour supply is exogenous. Investment is equal to the sum of government savings, household savings and net capital flows from abroad. In each sector, firms minimize their production costs with an assumption of perfect markets and constant return to scale technology. Modelling of international trade is based on the Armington assumption, which means that a domestically produced good is treated as distinct in preferences from the imported commodity produced by the same sector abroad. GEMINI-E3 incorporates a global constraint of foreign trade balance (zero or exogenous deficit) for each region. The trade balances are cleared through adjusting exchange rates. The government collects taxes and distributes the resulting revenues to households and firms through transfers and subsidies. The model is recursive dynamic, with backward looking (adaptive) expectations.

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	

4.2 The transport sector

By definition, macroeconomic models such as CGE models encompass the whole economy and cannot address each economic sector in detail. Another constraint is the statistical database of these models, based mainly on a social accounting matrix where the technological representation is weak and does not capture the existing and future technological options correctly. This is of course the case for the transport sector and especially for passenger vehicle transport. Indeed, in a standard CGE model, road transport is mainly based on petroleum fuel consumption and does not integrate alternative fuel vehicle technologies that are likely to change its technological paradigm in the next decades. In order to capture better 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 was represented by the submodule MARKAL-CHTRA, which allows the simulation of existing Swiss technical regulations for cars.

Another approach is to implement a technology-rich representation that addresses the main features of transport demand such as fleet turnover and alternative fuel vehicle choices directly into the CGE model. 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. Instead, only the main technological options that could be used in road vehicles within the next decades are described. Indeed, we want to show that a standard CGE model can be enriched at moderate cost with a view to estimating each main sector's contribution to a deep decarbonization pathway. This allows to show how the macroeconomic impacts of decarbonization depend on whether a sector contributes in proportion to its potentials or benefits from preferential treatment.

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

1. Land transport including 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 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 CES structure, together with housing demand and other consumptions. Next, we distinguish long distance travel, which is assumed air travel. The other trips (medium and short distances) can be made by 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 distance[3], and two other types using the same motorization (i.e. internal combustion), one using petroleum products and the other biofuels.

Each vehicle is characterized by a vehicle capital (called powertrain in Fig. 1) and a type of fuel used (refined oil, biofuel or electricity). The cost structure of each vehicle is calibrated from a bottom-up analysis performed by INFRAS (a Swiss research and consulting company). The model allows for substitution between types of vehicle but also within each type of vehicle between powertrain and fuel through the increase of capital expenses (i.e. improvements of the powertrain that do not represent a fundamental change of the technology). As the contribution of new types of vehicles (biofuel and electric) is rather marginal at present, we assume exogenous penetration of these vehicles is the reference scenario that is calibrated from INFRAS analysis. The different vehicles are produced by the same sector (i.e. other goods and services), and only the vehicle capital cost component differs. Biofuel is produced by the agricultural sector. A similar modelling approach is used regarding the transport done by firms mainly for freight.

4.3 Other important features

Electricity generation is represented by a nested CES function that includes the new capacities installed in renewable technologies, in addition to fossil fuels and nuclear and hydropower plants. Thermal fossil energy power generation is also represented by a nested CES function that combines coal, oil and natural gas power plants. Power generation is separated from the other activities (transmission and distribution) that appear through their factors of production at the top of the nesting structure of the electricity sector. As labour is of negligible importance for power generation[4], we retain only two factors of production: capital and fuels (capital only for renewables). GEMINI-E3 allows the use of carbon capture and storage (CCS) technology in electricity generation. This technology is implemented after 2030 when the price of carbon exceeds the cost of CCS. Rubin et al. (2015), based on a thorough analysis of the literature, estimate the mitigation costs in a range of 59 to 143 USD_{2013}/t of CO_2 avoided in new natural gas-fired combined-cycle power plants (GCCPP, the type that might be built in Switzerland) with capture and geologic storage. Therefore, in this paper, we suppose that CCS will begin to be implemented in Switzerland at a cost of 100 USD/CO_2. The CO_2 sequestration potential is significant in Switzerland, at around 2680 Mt CO_2 (Diamond et al. 2010).

---

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

[4] This not the case for electricity distribution, which is labour intensive.

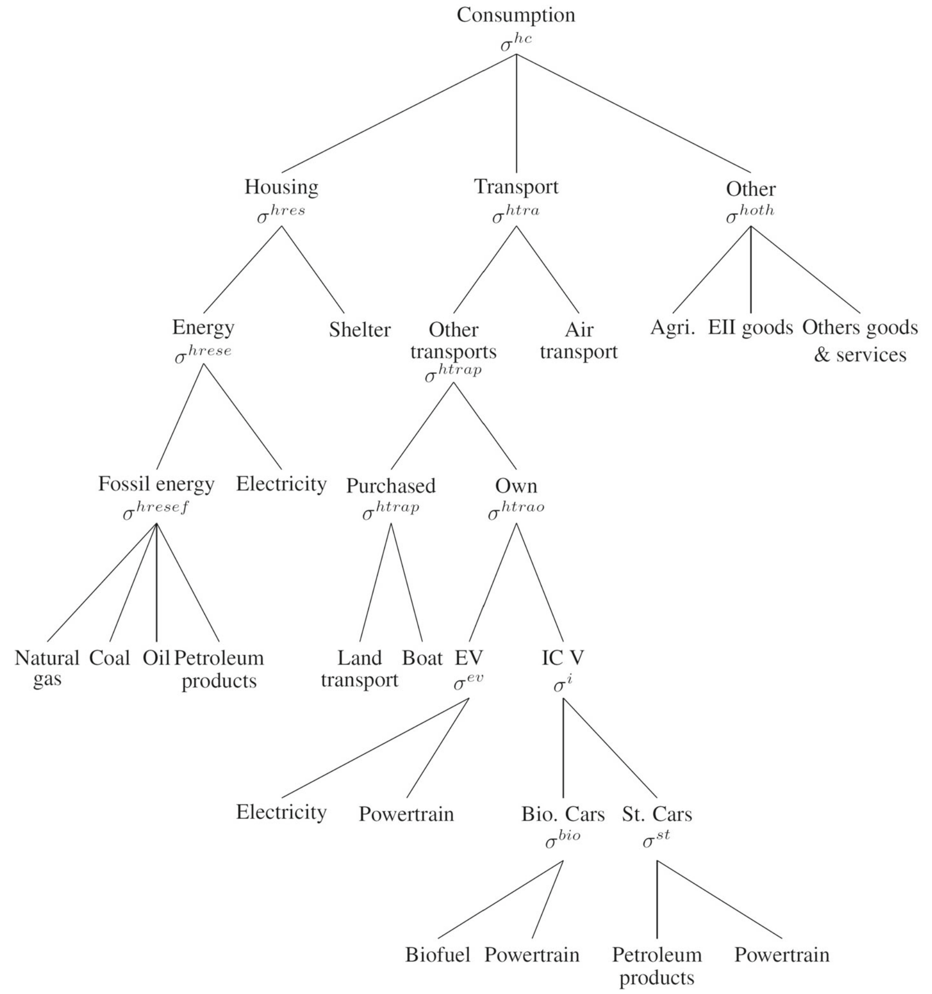

Fig. 1 Nested CES structure of household consumption

Switzerland opened its ETS in 2008 for large CO_2 emitters conducting one of a list of activities. Currently, 56 firms participate[5]. In our simulation, we consider that the following sectors participate in this market: the petroleum products sector (i.e. mainly refineries), the energy intensive industries and the electricity sector. For the last sector, we assume, in accordance with the current CO_2 Act, that GCCPP are not included in the ETS but rather continue to be required to compensate their emissions, with a minimum share of 50% domestic compensation[6]. The rest can be compensated internationally. 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 first present the reference scenario, and the SEMP decarbonization scenarios. We then detail the results of these scenarios.

5.1 Scenarios

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 heating degree-day follow these common assumptions. We assume that the CO_2 emissions standards for new vehicles will be 95 g of CO_2 per kilometre in 2020 and that they continue unchanged. For the other regions, we retain assumptions that are close to those of the World Energy Outlook 2015 (International Energy Agency 2015). In these other regions, following the SEMP assumptions, we do not assume any additional policies regarding climate change.

---

[5] Webpage of Federal Office for the Environment.

[6] The government's draft for climate policy after 2020 includes GCCPP into the ETS, but only if the Swiss ETS can be coupled with the European ETS, which is not approved yet and not assumed in our simulations.

In the reference scenario, the CO_2 levy (applied only on thermal fuel) reaches 120 CHF/t of CO_2 in 2018 and is kept constant thereafter. The ETS price increases over the simulation period in order to satisfy the annual CO_2 emissions reduction of 1.74% between 2013 and 2050 (i.e. a 48% reduction with respect to 2013 level). The path of CO_2 emissions results endogenously from these assumptions.

A first set of decarbonization scenarios are calibrated with a view to lower Swiss GHG emissions to 1.5 t of CO_2-eq per capita in 2050, a target set for the SEMP exercise and compatible with Switzerland's long-term goal. Translated in CO_2 emissions from energy combustion, this represents a target of 1.2 t of CO_2 per inhabitant, i.e. an abatement of 67% with respect to the 2015 level. A second set of scenarios aims at stronger abatement, such that GHG emissions do not exceed 1 t of CO_2-eq per capita in 2050. This is 78% below the 2015 level.

Following the guidelines of the SEMP exercise, three different simple policy designs are set-up to meet these targets:

- The first design (called "Uni") assumes that the existing carbon pricing, which combines a CO_2 levy on thermal fuels and an ETS price, is replaced by a uniform CO_2 levy on all fossil energy consumptions
- In the second design (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 design (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

The three designs are combined with the two targets to obtain six policy (or decarbonization) scenarios, as shown in Table 2. The same table gives also the Swiss carbon budget for each CO_2 target.

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. There are, of course, many other possible recycling schemes, which alter the impact of the policies on growth, sectors and welfare. However, the mode of revenue recycling is more important for distributional effects than for the total burden of a CO_2 price; the opposite is true for exemptions from a uniform CO_2 price of the types examined in this paper (Imhof 2012). For this reason, and because it is the predominant form of recycling for environmental taxes in Switzerland, the simple neutral format of lump-sum transfers was chosen in the context of the SEMP exercise.

5.2 The reference scenario

The equilibrium ETS price computed by GEMINI-E3 in response to the declining cap in the reference scenario is equal to 68 CHF/t of CO_2 in 2020 and rising gradually to 252 CHF in 2050 (see Table 3). These prices are much higher than the prices simulated for the EU-ETS by (Capros et al. 2016) despite an equal rate of price increase (from 8 € in 2015 to 90 € in 2050). The Swiss ETS does not start with a similar surplus of allowances from earlier phases, and the participating firms face higher abatement costs, as there exists relatively little heavy industry and no coal power plant in Switzerland.

The declining ETS cap and the constant 120 CHF/t CO_2 levy on thermal fuels lead to the path of CO_2 emissions shown in Fig. 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 t 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.

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

- A modal shift in favour of railway transport (consistent with the assumptions made in the Swiss energy perspectives (Prognos 2012))
- The improvement of the energy efficiency of vehicles
- The penetration of biofuel and electric vehicles in road transport

Figures 3 and 4 describe 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, electric passenger cars enter the market; their 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. Earlier, in 2030, these percentages are respectively equal to 5%, 4%, 5% and 4%.

Table 2 Policy instruments in the simulated scenarios and Swiss carbon budget in Mt CO_2

	CO_2 levy on thermal fuels	ETS	CO_2 levy on transport fuels
Reference scenario (1129 Mt CO_2)			
	120 CHF/t CO_2 constant	For large CO_2 emitters, with declining cap	Full exemption
1.5 t CO_2-eq scenarios (934 Mt CO_2)			
Uni	Endogenous so as to meet the 1.5-t target	No ETS	Same as thermal fuels
Uni-ETS	Endogenous so as to meet the 1.5-t target	Same as ref. scenario	Same as thermal fuels
Diff-ETS	Endogenous so as to meet the 1.5-t target	Same as ref. scenario	$\frac{1}{4}$ rate for thermal fuels
1 t CO_2-eq scenarios (852 Mt CO_2)			
Uni	Endogenous so as to meet the 1-t target	No ETS	Same as thermal fuels
Uni-ETS	Endogenous so as to meet the 1-t target	Same as ref. scenario	Same as thermal fuels
Diff-ETS	Endogenous so as to meet the 1-t target	Same as ref. scenario	$\frac{1}{4}$ rate for thermal fuels

CO_2 emissions from energy combustion from 2015 to 2050

5.3 The 1.5 t CO_2-eq per capita scenarios

Given the level of CO_2 emissions in the reference scenario, a 1.5-t target means 54% less emissions in 2050. The three policy designs presented in Section 5.1 are used to obtain these additional reductions. Figure 5 shows the resulting carbon emissions per sector. In comparison, the most ambitious scenario of the Energy Perspectives (Prognos 2012) lowers CO_2 emissions to 1.3 t per capita in 2050 or 11.4 million t (their Table 5-3). In this scenario, transportation accounts for 2.5 million tons (their Table 5-24). These numbers are close to those of our scenarios.

Figure 5 shows the resulting carbon emissions per sector, and Table 3 indicates the associated CO_2 prices and welfare costs expressed in percent of household consumption for the year 2050. The required carbon price may seem high, but it reflects the relatively low carbon intensity of the Swiss economy, which has little heavy industry and no electricity generation based on fossil fuels. Other simulations of decarbonization pathways have found that comparably high CO_2 prices are needed, for instance, 1100 CHF in Bretschger et al. (2011) and 1140 CHF in Ecoplan (2012). However, as pointed out by Landis et al. (2018), it is remarkable that in the context of the SEMP exercise and the "Uni" scenario, all models have very similar carbon taxes ranging from 529 to 652 CHF in 2050.

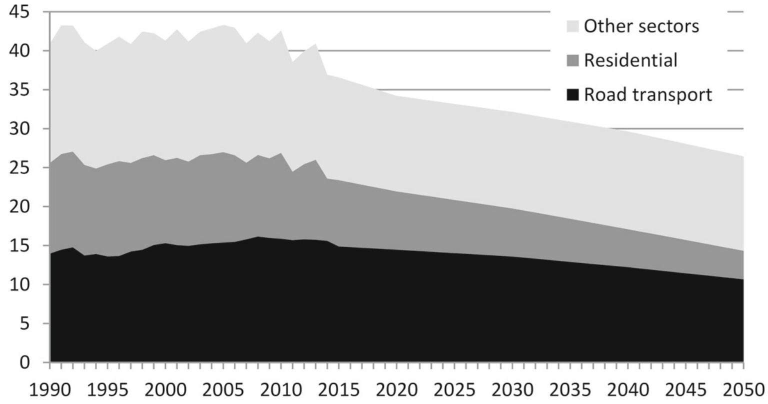

Fig. 2 CO_2 emissions from energy combustion (1A) in the reference scenario in Mt CO_2 (1990–2015: historical values)

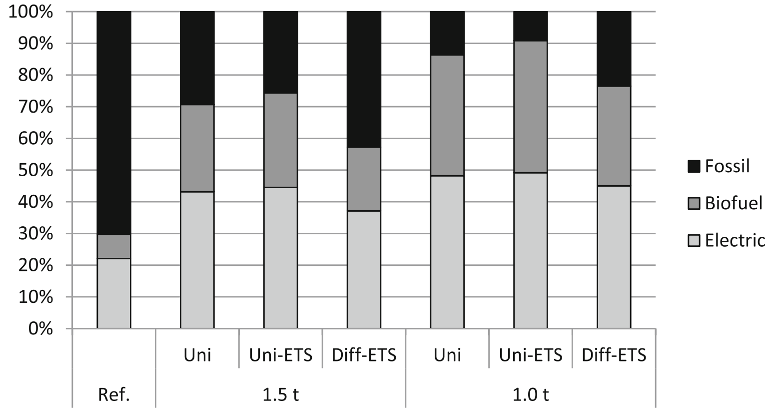

Fig. 3 Share of each vehicle type in distance travelled in percentage in 2050—cars

The scenario that combines an ETS market with a uniform price for thermal and transport fuels increases the welfare cost by 0.11% of household consumption or about 15% of the cost in the uniform tax scenario. Adding the preferential CO_2 tax treatment of motor fuels further raises the welfare cost by 0.16% of household consumption or about 19% of the cost of the scenario without that privilege. In both cases, the favourable treatment of some sectors requires much higher CO_2 taxes for the other sectors. Note that even in the "Diff-ETS" scenario the treatment of motor fuels is not as favourable as today (virtual exemption from carbon pricing) because this would make it nearly impossible to meet the ambitious reduction targets. The hierarchy between the scenarios is consistent with the results presented by Landis et al. (2018) in a similar context for Switzerland.

By definition, the emissions from the ETS sectors remain the same as those computed in the reference scenario when an ETS is implemented (see Fig. 5). However, the market-equilibrating ETS price is significantly lower than in the reference scenario (by more than 20%). Indeed, the decrease in oil product consumption leads to less output by refineries and hence less CO_2 in the petroleum product sectors. When the ETS sectors are subject to the uniform carbon price of the "Uni" scenario, they emit 36% less CO_2 than under the ETS regime.

Household mobility decreases by 6.5% in the "Uni" scenario. In the road transport sector, the scenario that assumes a uniform carbon tax on transport and thermal uses induces a significant penetration of biofuels as well as EV (see Figs. 3 and 4). CO_2 emissions from cars driven by households decrease by 60% in 2050. One third of this reduction (i.e. approximatively 20%) can be attributed to a decrease of car usage, partly compensated by more railway travel, which increases by 10%. The remaining two thirds of the reduction are mainly due to the penetration of electric and biofuel cars. Indeed, the decrease in emissions due to more efficient gasoline and diesel vehicles is rather limited; the scenario only adds 3% to

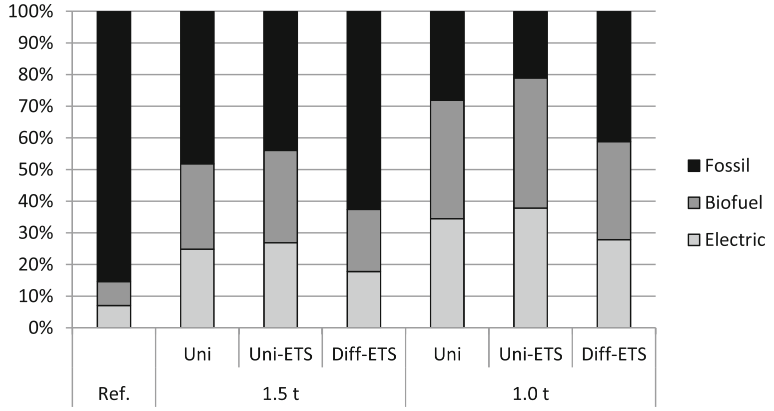

Fig. 4 Share of each vehicle type in distance travelled in percentage in 2050—other vehicles

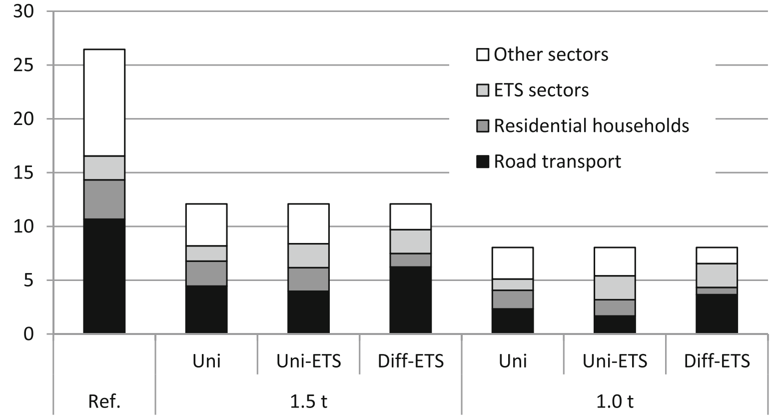

Fig. 5 CO_2 emissions in Mt CO_2 by sector in 2050

the fuel efficiency improvement happening in the reference scenario. Our results show that the technology improvements come mainly from fuel switching. 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 conflicts, 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 litre or 360 CHF/t 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/t. 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.

5.4 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 t 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.

Unsurprisingly, stronger abatement requires an increase of the CO_2 prices and leads to higher welfare costs. In the "Uni" scenario, the carbon price is equal to 1089 CHF/t of CO_2 in 2050, close to those computed by the other models involved in the SEMP exercise, which range from 970 to 1089 CHF (Landis et al. 2018). Nevertheless, the main findings of the previous scenarios remain unchanged. The most efficient scenario is still the uniform case, although the cost differences with the other scenarios increase with the degree of abatement.

For passenger vehicles, additional abatement is mainly obtained with biofuels. The share of distances travelled with biofuel cars increases from 28 to 38% in the "Uni" scenario when the target moves from 1.5 t CO_2-eq per capita to 1.0 t (see Fig. 3). The share of distances travelled

Table 3 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%

with electric cars increases only by 5 points (from 43 to 48%) between the two same scenarios. In contrast, for other vehicles, the shares of biofuel and electricity increase in the same proportions (see Fig. 4).

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 raises the burden for the other sectors. In these two scenarios, the ETS sectors accounts for 28% of CO_2 emissions in 2050, compared to 8% and 18% in the reference scenario and the ETS scenarios for the 1.5 t CO_2-eq goal. These sectors enjoy preferential treatment because energy costs have an impact on their international competitiveness, to which they are more exposed than the other sectors. GEMINI-E3 takes this international competition into account and yet finds that protecting these sectors through the ETS market results in an estimated overall welfare cost of 0.26% of household consumption, which is a high cost for protecting such a small part of the economy.

The conservation of a lower carbon tax for transport fuels (scenario "Diff-ETS") raises the required CO_2 tax on thermal fuels to 3175 CHF and induces welfare costs of 0.28% of household consumption in 2050, an impact of same magnitude as that of the ETS privilege (Table 3). In this scenario, fossil fuels still contribute 24% of the energy used by cars and 41% of the energy used by other road vehicles in 2050 (see Figs. 3 and 4). This is around double their shares if motor fuels were subject to the same carbon tax as thermal fuels.

6 Conclusion

Our simulations show that Switzerland can decarbonize, i.e. lower its energy-related CO_2 emissions to 1.5 t per inhabitant in 2050, by extending the existing CO_2 levy to all sources and raising it gradually from the current 82 CHF/t CO_2 to 652 CHF in 2050. This maximum levy would amount to about 1.50 CHF per litre of 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 and not strengthened. These firms would then pay a price per certificate of 193 CHF/t 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 a welfare cost between 0.74% of household consumption (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 t per inhabitant in 2050, which shows how steep the marginal abatement cost curve becomes for targets that are more aligned with 1.5 °C warming. This welfare cost increase is of limited magnitude in comparison with the additional efforts required to move from a 2 to 1.5 °C world, which have been estimated to cost 50 to 110% the cost of 2 °C by Rogelj et al. (2015). Note, however, that our simulations do not consider the costs of climate change nor the ancillary benefits of decarbonization. The advantage of the uniform tax scenario compared to the scenarios with preferential regimes is somewhat greater in the more ambitious programme. In addition, the preferential regimes concentrate the costs on non-ETS sectors and thermal fuels. Without tightening of its cap relative to the baseline, the ETS regime 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. Therefore, the two privileges—ETS and reduced CO_2 levy for motor fuels—have approximately the same welfare cost. The oft-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 levy 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 levy on transport fuels.

When they pay only one fourth of the rate of the ordinary CO_2 levy, fossil fuels are able to maintain their share in the energy mix for cars at 25% in 2050, even in the 1-t per capita scenario, compared to 70% in the reference scenario. Their share remains even at 40% for other road vehicles (85% in the reference scenario). These shares are divided by two in the absence of such preferential treatment.

However, our simulations show a significant penetration of electric and biofuel vehicles, even in the reference scenario. These changes will have to be supported by policies at cantonal and federal levels, per example, by promoting and financing electric vehicles charging infrastructure.

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 (Raubal et al. 2017), only a gradual penetration of electric vehicles and biofuels.

Abbreviations

BRIC: Brazil, Russia, India, China; CCS: Carbon capture and storage; CES: Constant elasticity of substitution; CGE: Computable general equilibrium; CHF: Swiss franc; Diff-ETS: Scenario of differentiated taxes with ETS; EII: Energy intensive industries; ETS: Emissions trading system; EU: European Union; EV: Electric vehicle; GCCPP: Gas-fired combined-cycle power plants; GDP: Gross domestic product; GHG: Greenhouse gas; IEA: International energy agency; MIT: Massachusetts institute of technology; SEMP: Swiss energy modeling platform; Uni-ETS: Scenario uniform with ETS; Uni: Scenario uniform; WEM: With existing measures

Acknowledgements
We thank the whole group of the SEMP exercise and in particular Adriana Marcucci and Florian Landis for the coordination and the management of the project.

Authors' contributions

The two authors have contributed to the paper and the work attached to it. Both authors read and approved the final manuscript.

Funding
The research presented in this paper did not receive any funding.

Availability of data and materials

The model used in this paper is described in Bernard and Vielle (2008). The changes that have been made with respect to this version especially regarding the transport sector are described in Section 4. The results of the scenarios presented in this paper should probably be available within a website dedicated to the SEMP scenarios.

Competing interests

The authors declare that they have no competing interests.

Received: 18 December 2017 Accepted: 30 July 2019

References

Abrell, J. (2010). Regulating CO_2 emissions of transportation in Europe: A CGE-analysis using market-based instruments. *Transportation Research Part D: Transport and Environment*, *15*(4), 235–239.

Alberini, A., Bareit, M., Filippini, M. (2016). What is the effect of fuel efficiency information on car prices? Evidence from Switzerland. *The Energy Journal*, *37*, 315–342.

ARE (2016). *Perspectives d'évolution du transport 2040*. Bern: Swiss Federal Office for Spatial Planning.

Aguiar, A., Narayanan, B., McDougall, R. (2016). An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis*, *1*(1), 181–208.

Berg, C. (2007). Household transport demand in a CGE-framework. *Environmental and Resource Economics*, *37*(3), 573–597.

Bernard, A., & Vielle, M. (2008). GEMINI-E3, a general equilibrium model of international national interactions between economy, energy and the environment. *Computational Management Science*, *5*(3), 173–206.

Betschart, M., Schäppi, B., Iten, R., Füssler, J., Vielle, M., Thalmann, P. (2016). *Emissions scenarios without measures, 1990-2030*. Zürich and Lausanne: Report for Swiss Federal Office for the Environment.

Bretschger, L., Ramer, R., Schwark, F. (2011). Growth effects of carbon policies: Applying a fully dynamic CGE model with heterogeneous capital. *Resource and Energy Economics*, *33*(4), 963–980.

Capros, P., et al. (2016). *EU reference scenario 2016: energy, transport and GHG emissions - trends to 2050, Eur. Community 27*. https://doi.org/10.2833/9127.

Diamond, L.W., Leu, W., Chevalier, G. (2010). *Potential for geological sequestration of CO_2 in Switzerland, Tech. rep.* Bern: Swiss Federal Office of the Energy.

EBP (2017). *Energieverbrauch und energieeffizienz der neuen personenwagen 2016*. Bern: Report for Swiss Federal Office of Energy.

Ecoplan (2012). *Energiestrategie 2050 - Volkswirtschaftliche Auswirkungen. Analyse mit einem berechenbaren Gleichgewichtsmodell für die Schweiz*. Berne: Report for Swiss Federal Office of Energy.

European Commission (2016b). *A European strategy for low-emission mobility, SWD(2016) 244 final*. Brussels: European commission.

Imhof, J. (2012). Fuel exemptions, revenue recycling, equity and efficiency: Evaluating post-Kyoto policies for Switzerland. *Swiss Journal of Economics and Statistics*, *148*(2), 197–227.

INFRAS (2017). *Pilotstudie zum Treibstoffverbrauch und den Treibhausgasemissionen im Strassenverkehr 1990-2050*. Bern.

International Energy Agency (2009). *Transport, energy and CO_2. Moving toward sustainability*. Paris: Éditions OCDE. https://doi.org/10.1787/9789264073173-en.

International Energy Agency (2015). *World energy outlook 2015*. Paris: International Energy Agency publication.

Kannan, R., & Hirschberg, S. (2016). Interplay between electricity and transport sectors - Integrating the Swiss car fleet and electricity system. *Transportation Research Part A: Policy and Practice*, *94*(Supplement C), 514–531.

Karkatsoulis, P., Siskos, P., Paroussos, L., Capros, P. (2017). Simulating deep CO_2 emission reduction in transport in a general equilibrium framework: The GEM-E3T model. *Transportation Research Part D: Transport and Environment*, *55*, 343–358.

Karplus, V.J., Paltsev, S., Babiker, M., Reilly, J.M. (2013). Applying engineering and fleet detail to represent passenger vehicle transport in a computable general equilibrium model. *Economic Modelling*, *30*(Supplement C), 295–305.

Landis, F., Marcucci, A., Rausch, S., Kannan, R., Bretschger, L. (2018). Multi-model Comparison of Swiss Decarbonization Scenarios. *Swiss Journal of Economics and Statistics*. Submitted.

Landis, F., Rausch, S., Kosch, M. (2018). Differentiated carbon prices and the economic cost of decarbonization. *Environmental and Resource Economics*, *70*(2), 483–516.

Nathani, C., Sutter, D., van Nieuwkoop, R., Peter, M., Kraner, S., Holzhey, M., Rütter, H., Zandonella, R. (2011). *Energy related disaggregation of the Swiss Input-Output Table, Tech. rep.* Bern: Swiss Federal Office of Energy.

Pietzcker, R.C., Longden, T., Chen, W., Fu, S., Kriegler, E., Kyle, P., Luderer, G. (2014). Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy*, *64*, 95–108.

Prognos (2012). *Die Energieperspektiven für die Schweiz bis 2050 - Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050, Tech. rep.*: Study commissioned by the Swiss Federal Office of Energy, Basel.

Raubal, M., Jonietz, D., Ciari, F., Boulouchos, K., Küng, L., Georges, G., Hirschberg, S., Schenler, W., Cox, R.K.B., Rudel, R., Cellina, F., Kovacs, N., Michl, M.H.T. (2017). *Towards an energy efficient Swiss transportation system, Tech. rep.* Zürich: SCCER Mobility.

Robson, E., Wijayaratna, K., Dixit, V. (2018). A review of computable general equilibrium models for transport and their applications in appraisal. *Transportation Research Part A: Policy and Practice*, *116*, 31–53.

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, *5*, 519–527.

Rubin, E.S., Davison, J.E., Herzog, H.J. (2015). *The cost of CO_2 capture and storage* Vol. 40, (pp. 378–400). special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO2 Capture and Storage.

Sceia, A., Altamirano-Cabrera, J.C., Vielle, M., Weidmann, N. (2012). Assessment of acceptable Swiss post-2012 climate policies. *Swiss Journal of Economics and Statistics (SJES)*, *148*(II), 347–380.

Schäfer, A., & Jacoby, H.D. (2005). Technology detail in a multisector CGE model: transport under climate policy. *Energy Economics*, *27*(1), 1–24.

Schäfer, A., & Jacoby, H.D. (2006). Vehicle technology under CO_2 constraint: A general equilibrium analysis. *Energy Policy*, *34*(9), 975–985.

The International Council on Clean Transportation (2016). *European Vehicle Market Statistics - Pocketbook 2016/17*. Berlin.

Vielle, M., & Thalmann, P. (2017). *Updated emissions scenarios without measures, 1990-2025, Tech. rep.* Bern: Swiss Federal Office for the Environment. EPFL.

Vöhringer, F., Stocker, D., Knoke, W. (2016). *Intended Nationally Determined Contributions (INDCs) under the Paris Agreement on Climate Change: Fact sheets for selected countries and assessments of underlying efforts*. Bern: Federal Office for the Environment. Econability.

Publisher's Note