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Cost distribution and equity of climate policy in Switzerland

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Abstract

Swiss targets for climate policy require significant reductions of emissions by 2050. While such reductions can be achieved in a cost-efficient manner by employing taxes on greenhouse gas emissions, such taxes tend to lead to a regressive distribution of policy cost among households. To counteract such a regressive outcome, tax revenue may be recycled in a progressive way. This paper uses a computable general equilibrium model coupled with a microsimulation of household income and expenditure to examine the policy cost of different carbon tax policies and their distribution across households. I find that in the absence of revenue recycling, emission taxation leads to a regressive distribution of policy cost. I analyze different revenue recycling schemes (per-capita lump-sum transfers, reductions in labor taxation, and reductions in VAT taxation of necessary commodities) and their ability to avoid regressive outcomes.

Keywords: Cost-effectiveness, Computable general equilibrium, Microsimulation, Climate policy, Distributional impacts

1 Introduction

Different policy options are often compared based on their aggregate cost. In the context of environmental policy, this may not only include the choice of the primary policy instrument for correcting the environmental externality but also the mechanisms to compensate additional spending (in the case of subsidies for environmentally friendly behavior) or revenue (in the case of taxes on polluting activities) by the government from the primary instrument. The literature on the double dividend (Goulder, 1995) has found that the mechanisms for revenue-redistribution can play an important part in keeping overall costs of pollution taxes low. At the same time, it has been recognized that questions of political feasibility, which depend to a large part on the distribution of policy costs across economic agents, competes with overall efficiency for determining the preferred policy (Bovenberg, 1999).

One concern is that if the government taxes the use of greenhouse gas (GHG) emitting fossil fuels, low-income households might pay a disproportionately high share of the policy's cost (Carattini et al., 2017). Analyses of household expenditures indicate that low-income households spend a larger share of their overall expenditures on energy than do households with a higher income in some cases (this depends on country and fuel that are considered) but not in others (Sterner, 2012; Decoster, 1995). In any case, regressive impacts on the expenditure side can be reversed when taking into account revenue recycling options and impacts of policies not only on consumer prices, but also on income. Rausch et al. (2011) highlight the importance of including effects on income effects using a computable general equilibrium (CGE) model of the US economy. And several studies in the European context show that revenue recycling has a crucial effect on overall distributional outcome (e.g., Landis and Heindl, 2016; Speck, 1999).

With this paper, I contribute to the study of the trade-off between efficiency and equity in designing tax-based climate policy. I couple a CGE model with a microsimulation of household expenditure which gives household level detail in its impact assessment. Employing a social welfare function that incorporates inequality aversion, I am able to show how equity concerns influence the ranking of policy options. While this framework has been previously applied elsewhere (see Böhringer et al., 2017),

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this is the first such analysis in the context of Swiss climate policy. I attempt the first comparison of different revenue recycling options within this framework.

In the Swiss context, Imhof (2012) and Böhringer and Müller (2014) studied the trade-offs between efficiency and equity in designing tax-based climate policy. Using a CGE model of Switzerland and representing household consumption by 5 income quintiles (Böhringer and Müller, 2014) detect a trade-off between efficiency and equity. If carbon tax revenue is used to reduce income taxes, employment increases, which is efficient on the national level, but most of these benefits go to high-income households. Their analysis does not use a social welfare function that takes equity concerns into account, and it cannot rank policies due to this trade-off. Imhof (2012) uses a CGE model representing household consumption by representative agents corresponding to 10 income deciles of working age households and 4 income quartiles of retired households. He finds a trade-off between equity and efficiency as well and uses different assumptions about the appropriate inequality aversion to calibrate welfare functions. If inequality is an issue, it is the recycling scheme with the highest aggregate cost that should be chosen. When using welfare functions that take equity concerns into account combined with rough aggregates of households, however, variation of income and policy impacts within those aggregates is averaged out. Still, in agreement with Imhof's study, my results indicate that revenue recycling via per-capita lump-sum transfers is not the most efficient in terms of aggregate productivity but becomes the preferred among the considered choices if equity is of concern. This can be seen as vindication of the current practice of recycling part of the revenue from climate taxation by lump-sum per-capita refunds to personal health insurance bills.[1] My results highlight the importance of considering disaggregated households rather than household aggregates when analyzing inequality questions. Also, my results show that the design of revenue recycling may be as important as the concrete design of carbon tax policy if inequality aversion is of concern.

The outline of the remainder of the paper is as follows. In Section 2, I describe the numerical framework which is used to compare the different policy options. Section 3 describes the policy scenarios that are considered in the analysis. Section 4 presents the results of the numerical analysis, and in Section 5, I summarize the main conclusions and compare them with the actual Swiss policy design.

2 Model and data

This section provides an overview of the quantitative framework which integrates an economy-wide multi-sector general equilibrium model with a microsimulation analysis of households and has been previously employed by (Landis et al., 2017). I first describe the various data sources used for calibration of the model. A brief description of the model structure and the computation method for solving the economic equilibrium model with a very large number of households are as follows.

2.1 Data

The numerical model employed in this study is based on national accounts and household survey data. National accounts provide information on value flows between different sectors of the economy, households, and the government. Household survey data indicates how aggregate household expenditure for different commodities and income from different production factors are distributed among single households. The two data sources were harmonized to construct a balanced set of accounts for the model's base year.

2.1.1 National economic accounts and energy data

For the aggregate Swiss economy, value flows are given by the social accounting matrix (SAM) and are complemented by physical energy flow data in the "National Accounting Matrix including Environmental Accounts (NAMEA)" (Nathani et al., 2013). The SAM provides information on economic transactions among firms, households, and government agents. The physical energy flow data allow for inferring CO_2 emissions associated with energy demand.

In its original form, the SAM distinguishes 66 industries and commodity groups and 20 categories for final demand. Table 1 provides an overview of the model's commodity aggregation. I identify 11 sectors of energy supply and conversion separating various fuels (motor fuels, heating oil, natural gas, coal, crude oil) and secondary energy carriers (comprising various forms of electricity and heat). The choice of aggregation for the 21 non-energy sectors is guided by the considerations to separately identify sectors which are large in terms of economic size (i.e., contribution to gross value-added), exhibit a high-energy intensity, or sectors that are targeted with specific policy measures (for example, private transportation, household energy demand, and industrial sectors). Three accounts of final demand represent private and government consumption, and investment. The social accounting data further provides payments of payroll taxes, income taxes, value-added taxes, import tariffs by commodity, sector-specific output taxes, subsidies, and energy-related taxes including mineral oil taxes.

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[1] About one third of carbon tax revenue is used to finance the Swiss Building Program, which subsidizes investments in improved insulation and non-fossil-based heating systems. From the remainder, the part of the revenue from taxing *household* fuel use is recycled to inhabitants via this per-capita lump-sum rebate (https://www.bafu.admin.ch/co2-abgabe).

Table 1 Overview of model resolution: sectors, electricity generation technologies, and household groups

Sectors ($i \in I$)	
Non-energy	Agriculture (agr), Paper* (pap), Chemicals* (che), Plastics* (pla), Other non-metallic mineral products* (nme), Basic metals* (bme), Fabricated metal products* (fmp), Medical and precision instruments (med), Manufacturing (man), Machinery and equipment (mch), Office machinery, computers (omc), Radio, TV and communication equipment (elt), Trade and repair except motor vehicles (wht), Real estate (est), Services (ser), Construction (cns), Final demand public/purchased transport (trc), Intermediate transportation services (try), Motor vehicles, trailers (veh), Trade and repair of vehicles; retail sale of automotive fuel (trd), Air transportation* (atp)
Energy supply and conversion	Motor fuels (benz), Heating oil (hoil), Other mineral oil products (omop), Nuclear fuel (nuc), Crude oil (cru), Coal* (coa), Natural gas (gas), Electricity generation* (ele), Electricity distribution & transmission (edt), Electricity from waste incineration* (ewi), Heat from waste incineration* (hwi)
Final demand	Private consumption by representative household, government consumption, investment demand
Electricity generation technologies ($p \in P$)	Hydro power, Nuclear power, Power from fossil fuels, Power from renewable energy sources

*Indicates sectors that are subject to the Swiss Emissions Trading System (ETS) which covers energy-intensive industries

2.1.2 Micro-household data and data reconciliation

On the household side, a representative sample of the Swiss population of households is portrayed by the 2009–2011 Swiss Household Budget Survey "Haushaltsbudgeterhebung." The HABE survey is conducted on an annual basis by the Swiss Federal Statistical Office (BFS). It collects information for roughly 3000 households on expenditure patterns and income sources. Household data is weighted according to the inclusion probability.[2] The weights are adjusted for sampling bias and calibrated to the observed distribution of the Swiss population (BFS, 2007). To increase the sample size, the underlying data set aggregates three waves of survey data from the consecutive years 2009–2011 (BFS, 2012a, 2012b, and 2013) using annual weights. Thus, a set of 9734 observations of household accounts are available to describe household expenditure and income in the model. Besides the information on income expenditure, the HABE data include other information such as household composition, age of household members, urbanization degree, and ownership status of housing.

The weighted sum of income and expenditures of households reported in HABE has to be reconciled with the national accounts in the SAM. A match between national aggregates and household-based data in the base year calibration of the model is required for consistent evaluation of counterfactual scenarios.[3] In a first step, missing data are imputed based on information about households' expenditures and socio-economic characteristics (income, renting or owning a house, etc.).[4] In a second step, the national consumption in terms of COICOP "Classification of Individual Consumption According to Purpose" categories was then imposed on the household data by scaling the weighted household consumption from the survey by the respective factor for each consumption category. Similarly, household data on wage income was scaled to meet the national aggregate.[5] Transfers are also in the household survey and were scaled to match aggregate transfers between households and the government from the SAM. The remaining difference between income and expenditure of households was attributed to (dis-)savings. The different adjustments that had to me made are summarized in Table 12 in Appendix 3.

2.2 Model overview

Herein, I briefly outline the main key features of the numerical model. Appendix 3 contains a complete algebraic description of the model's equilibrium conditions.

2.2.1 Heterogeneous households

All 9734 households from the HABE survey are represented as individual economic agents in the general equilibrium model. This enables me to account for the heterogeneity of the entire Swiss household population along the two dimensions, expenditure and income. The utility functions of households are calibrated such that the observed expenditures at initial prices according to the (harmonized) HABE data are consistent with utility

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[2] The inclusion probability of a member of the population is its probability of becoming part of the sample during the drawing of a single sample.

[3] The aggregated household consumption in the HABE and SAM accounts can differ significantly for several reasons: (i) missing households: in contrary to the national accounts, the HABE data does not consider non-profit institutions serving households (NPISH) and collective households; (ii) differences in definition of cost (for example, health care and education expenditure); (iii) missing response on certain questions; and (iv) misreported items (for example, expenditures on alcohol).

[4] For more information on imputation techniques, see, for example, Bethlehem et al. (2011) and Rubin (1987). Imputation was used to correct incomplete observations in the HABE data with respect to thermal fuel consumption of households, for which an unrealistically high share of households does not report any spending.

[5] Operating surplus of economic sectors includes profits that are directly reinvested, and thus, a direct link to capital rents of investors cannot be made. Based on historical observations, about half of the operating surplus generates actual income to households, while the remainder is directly reinvested.

maximization of households given market prices. Labor supply, endowments of capital, and entitlements to government transfers are distributed such that the income patterns in the HABE data are achieved.

For counterfactual scenarios, the model fixes labor supply and savings at business-as-usual levels. Household savings are used for purchasing a composite investment good. Given goods' and factors' prices, households maximize their utility by allocating income received from government transfers, wages, and rents on capital to consumption. Utility from consumption is described by a nested constant-elasticity-of-substitution (CES) utility function (see the upper panel in Figure 8 in Appendix 3). The utility function uses the same elasticities of substitution for all households, and in order to capture the increasing ability in the long term to adopt to fundamental economic change, select elasticities are set higher in 2035 and 2050 than up to 2020. The specific elasticities of substitution in household consumption can be found in Table 11 in Appendix 3.

2.2.2 Production technologies and firm behavior

In each industry, gross output is produced using primary inputs of labor and capital together with intermediate inputs that are composed of domestically produced goods and imported goods. The model employs CES functions to characterize the substitutability between inputs of production (see the lower panel in Figure 8 in Appendix 3). Given input prices (gross of taxes and subsidies), firms minimize production costs subject to physical technology constraints. Firms operate in perfectly competitive markets selling their products at a price equal to marginal costs. Capital and labor are assumed to be mobile across Swiss industries. I assume that Swiss and foreign investors view investments inside or outside Switzerland as perfect substitutes. This implies that rents on capital are determined by the international interest rate on which Swiss policy has no effect.

Power generation is modeled using a compact bottom-up activity analysis representation where discrete technologies produce a homogeneous electricity good by combining technology-specific capital with inputs of labor, fuel, and materials. The substitution elasticity between technology-specific capital, and the composite inputs is chosen to match exogenous technology-specific price elasticities of supply. The national accounts provide data to calibrate production functions for electricity-generating technologies that have been active in the base year 2008: hydro power, nuclear power, power from renewables, and power from fossil fuels.

2.2.3 Government activity

A single government entity represents government activities at all levels—federal, cantonal, and local—as well as part of the social security system. The government collects taxes to finance transfers and the provision of a public good. Besides value-added taxes, income taxes, corporate profit taxes and social security contributions, the model features industry-specific output taxes, and subsidies as well as import and export levies. The public good is produced with commodities purchased at market prices. The economic impact assessment of different policy scenarios always involves revenue-neutral tax reforms in order to keep the provision of the public good constant. Thus, I can provide a meaningful welfare comparison without the need to trade off private and government (public) consumption. Revenue neutrality is achieved by endogenously setting aggregate amounts of lump-sum transfers between the government and households. The lump-sum transfers are allocated among households in proportion to base year household consumption.[6]

2.2.4 International trade and model closure

With the exception of crude oil, which is treated as a homogeneous good, domestic and imported varieties of the same good are differentiated following the Armington (1969) assumption (i.e., for each commodity, its total market supply is a CES composite of a domestically produced variety and an imported variety). In analogy to the import side, domestically produced goods are converted through a constant-elasticity-of-transformation function into goods destined for the domestic market and the export market, respectively.

In international trade, Switzerland is assumed to be small, implying that the levels of Swiss exports and imports do not affect world market prices. Switzerland holds its balance-of-payments (measured in foreign exchange) constant across policy scenarios, and the exchange rate adjusts endogenously to reflect changes in terms of trade.

3 Scenarios

The analysis conducted for this paper establishes a business as ausual (BAU) scenario in which currently implemented policies are assumed to be continued. The model is calibrated to assumptions about how energy prices and demand develop under the currently implemented policies. Counterfactual scenarios then implement different additional policies for reaching targets of Swiss energy and climate policy and compare socio-economic outcomes in these counterfactual scenarios with the outcomes in the BAU.

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[6] This mechanism for ensuring revenue neutrality balances the national budget but not necessarily budgets at the cantonal level. My model neglects the changes in cantonal revenue from changes in wages and capital rents and thus income tax payments. Due to different income tax rates, different cantons are affected to different degrees by these tax revenue impacts of climate policy. As it stands, my model generates results that could only be achieved if additional transfer payments between cantons would be enacted.

Independent of the considered policy scenario, the Swiss economy is facing world market prices for trade in energy goods and population growth as given in Table 2. Population growth was used to compute the total CO_2 emission targets for Switzerland from the per-capita targets currently specified.[7]

3.1 Business-as-usual (BAU) scenario

The BAU includes all currently implemented policies for reducing CO_2 emissions in Switzerland. Some instruments such as the “Gebäudeprogramm/Programme Bâtiments” (subsidies on buildings insulation) and the “Wettbewerbliche Ausschreibung/Appels d’offres publics” (competitive bidding for state support of energy efficiency measures) but also efficiency standards on vehicles and appliances are not explicitly implemented in the CEPE-HH model but have implicit consequences on the adopted assumptions about energy demand over time in the BAU. Price-based policies such as electricity and CO_2 taxes are explicitly modeled, and the model is calibrated such that BAU energy demand trends are consistent with BAU CO_2 prices (both given in Table 3). The Swiss Emission Trading System (CH ETS) is assumed to remain uncoupled with the European Emission Trading System (EU ETS) in the BAU scenario. Energy demand by ETS sectors has been calibrated such that the scenario trajectories of fossil fuel demand within the ETS sectors (see fourth line in Table 3) would be consistent with EU ETS market prices (fifth line in Table 2). As these trends for fossil energy demand imply emissions in excess of what the cap for the CH ETS foresees, the model, by restricting ETS emissions to the cap, determines the endogenous ETS permit prices in Switzerland in the BAU scenario.

Distributional impacts of carbon taxes are to a large extent determined by how much households spend on fossil fuels and thus by how much they emit. Figure 1 shows shares of household expenditures going toward fossil fuels where households are grouped by income quintile. The fact that low-income households tend to spend large shares on fossil fuels implies that a carbon tax without appropriate corrective revenue recycling results in a regressive distribution of policy cost.

The point that this study makes is that the distribution of policy cost relative to baseline household welfare depends on the revenue recycling scheme that is used. The impacts of different revenue recycling schemes, in turn, depend on household size if revenue recycling is per-capita-based, on labor income if revenue recycling reduces labor taxes, and on expenditure for certain goods if revenue recycling reduces VAT on those goods. Appendix 1 shows how these indicators are distributed across income in the BAU.

Table 2 Time trends of exogenous parameters facing the Swiss economy in all scenarios

	2010	2020	2035	2050
Population (million)	7.79	8.68	9.8	10.3
Crude oil price (2010 US$/barrel)	78	105	120	129
Gas price (2010 US$/MBtu)	7.5	10.4	11.7	12.4
EU electricity prices (2013 €/MWh)	133	150	160	159
EU ETS permit price (2010 €/tCO2e)	15	15	57	239

Note: Scenario drivers were given by the Swiss Energy Modelling Platform (SEMP). For sources of scenarios see Landis, Marcucci, et al. (2018)

3.2 Counterfactual scenarios

15TPC The policy target in this scenario is to reduce emissions to 1.5 metric tonnes of CO_2 equivalent (tCO2e) per capita across the Swiss population. The target is reached by an perfectly informed government that sets a uniform carbon tax such that the target for 2050 is reached. For the years leading up to 2050, a succession of annually decreasing emission targets are given by the scenario (see Table 4). Revenue from carbon taxation of industries is returned to them via a reduction of social contribution in proportion to their wage bills. Revenue from taxing CO_2 emissions by households is returned as a per-capita lump-sum transfer.

10TPC Same as 15TPC but with annual targets leading up to 1.0 tCO2e per capital in 2050. Emission targets for 2035 and 2050 relative to 2010 are given in Table 4.

XXTPC_etsUni Scenarios 15TPC_etsUni and 10TPC_etsUni reach the same targets as scenarios 15TPC and 10TPC, but different policies are implemented: An emissions trading system (ETS) caps the emissions of industrial sectors included in the system while the government sets uniform CO_2 taxes outside the ETS such that the overall emission target of the respective scenario is met.

Table 3 Time trends of Swiss economic indicators and policies in the BAU scenarios

	2010	2015	2035	2050
GDP (relative to 2010)	1	1.046	1.43	1.66
Energy demand (rel. 2010)	1	0.92	0.839	0.782
Electricity demand (rel. 2010)	1	0.996	1.097	1.175
Fossil energy demand in ETS (rel. 2010)	1	0.876	0.621	0.388
CO_2 tax on thermal fuels (CHF/tCO_2)	36	60	120	120
CO_2 tax on motor fuels (CHF/tCO_2)	0	0	0	0
Cap in Swiss ETS (relative to 2013 emissions)	NA	0.965	0.617	0.356

Note: Scenario drivers were given by the SEMP. For sources of scenarios, see Landis, Marcucci, et al. (2018). CHF denotes the currency Swiss Francs

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[7] The growth of (the effective value of) the labor force was chosen in line with BAU growth of gross domestic product (GDP), on the other hand.

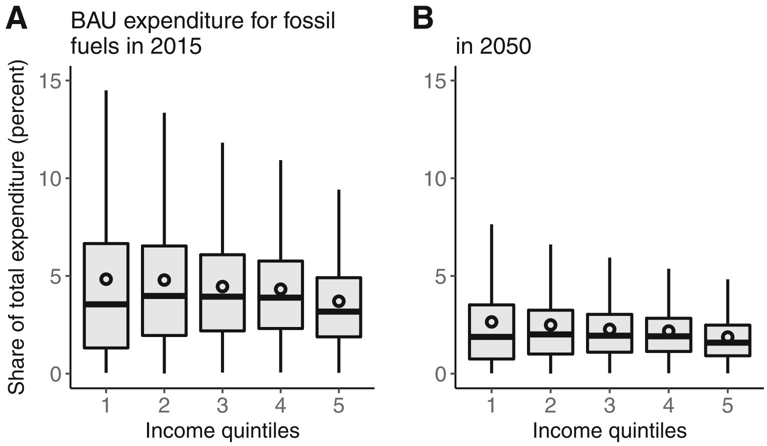

Fig. 1 Distribution of fossil fuel expenditure share within and across income quintiles in 2015 (**a**) and 2050 (**b**). Note: Income quintiles are according to allocation by statistical office. Circles show mean values

XXTPC_etsDiff Scenarios 15TPC_etsDiff and 10TPC_etsDiff resemble scenarios 15TPC_etsUni and 10TPC_etsUni, but instead of taxing emissions outside the ETS uniformly, they put a four times lower tax on motor fuels than on thermal fuels. The absolute level of the taxes in each year is again chosen to meet the annual emission targets.

XXTPC_etsXxx_LT Instead of a lump-sum transfer for recycling revenue from taxing GHG emissions by households, these scenarios employ a reduction of labor taxation for returning the revenue. Note that these taxes do not influence labor supply decisions in my model and thus do not create the efficiency gain expected in the double-dividend literature.[8]

XXTPC_etsXxx_VAT Instead of a lump-sum transfer for recycling revenue from taxing GHG emissions by households, these scenarios employ a reduction of the VAT rate for the commodities `AGR` and `TRC` for returning the revenue. `AGR` and `TRC` are the two commodities that my model resolves for which VAT is clearly regressive: low-income households tend to spend a larger share of their expenditures on these goods than do high-income households. I show the expenditure shares across income quintiles in Figure 6 in Appendix 1.

It is important to note that revenue recycling does not make carbon policy revenue-neutral. While the recycled amount compensated the revenue from carbon taxation, climate policy impacts other revenue channels of government income. In order to compensate these changes, the government in the model levies a uniform tax on income net of baseline taxes. As it is unclear what measures the Swiss government would employ in the real world to balance its budget, this method of balancing government income is chosen to make sure that budget balancing does not have biased impacts on the distributional outcome of the scenario results.

4 Results

Before showing and discussing results on equivalent income and social welfare, I shall highlight the amount of revenue that is generated by the carbon tax in the different scenarios and what changes in tax rates or transfers this results in (see Table 5). The first row shows that rates for the economy-wide uniform taxation of carbon do not change much across different recycling mechanisms and that they reach just below CHF 950 per tCO_2 in 2050 in the case of the ambitious target of scenario 10TPC. The revenue that is recycled on the household side is shown in the following rows for the different schemes of carbon taxation, uniform, etsDiff, and etsUni. The variation across taxation schemes of the amount of money for recycling is reflected in different results for the recycling mechanisms. The third row from the bottom shows that per-capita lump-sum transfers might reach as high as CHF 440 per annum by 2050 with the ambitious target of the 10TPC scenario. To compare this with transfers from the current CO_2 levy, consider that it has been determined that

Table 4 Emission targets for policy scenarios

Target (relative to 2010)	2010	2035	2050
15TPC	1	0.571	0.284
10TPC	1	0.510	0.189

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[8] The standard way to model labor supply decisions is to include leisure time in consumer utility. This then creates a trade-off between leisure and labor, resulting in labor supply responses to changes in wages. I cannot calibrate the value of the full-time endowment on the household level as the household's labor supply in hours, and thus, the value to the household of 1 h is unknown.

Table 5 Carbon taxes, volumes of revenue for recycling, and the resulting changes in recycling mechanisms for the different scenarios

		2035		2050	
		15TPC	10TPC	15TPC	10TPC
Carbon tax (CHF/tCO2)	uniform	234–235	336–339	516–517	943–946
Revenue (billion CHF)	uniform/LS	3.19	4.03	3.56	4.47
	etsDiff/LS	2.89	3.71	3.35	4.05
	etsUni/LS	3.38	4.31	3.64	4.51
LS: transfers	(CHF)	295–345	379–440	326–353	393–438
LT: reduction	% change	0.7–0.9%	1.0–1.1%	0.7–0.8%	0.9–1.0%
VAT reduction	% change	2.1–2.5%	2.7–3.2%	2.1–2.3%	2.5–2.8%

Note: The ranges of carbon tax rates on the first row cover the different recycling mechanisms LS, LT, and VAT for an economy-wide uniform carbon tax. The ranges of transfers and tax reductions (three bottom rows) cover the different carbon tax schemes uniform, etsDiff, and etsUni

in 2019, the per-capita refund shall be CHF 76.80.[9] The bottom two rows show the reductions in the taxation of labor and VAT. Labor tax reductions do not exceed 1.1 percentage points, which leaves positive contributions to social security if this is deducted from the current rate of contribution of 5.625% or more that employees have to pay.[10] VAT reductions on the other hand go as high as 3.2 percentage points. Given that this reduction is applied to agricultural products (`AGR`) among others, the going VAT rate on which is 2.5%,[11] this would lead to negative VAT taxation, thus ruling out the proposed VAT recycling as a practicable way of recycling carbon tax revenue in practice. The recycling via VAT could, however, be modified to yield lower percentage point reductions by including more commodities for the reduction of the VAT.

When reporting results on how the different policy options perform, I first discuss scenario outcomes in terms of mean income (MI), a measure of macroeconomic production efficiency that does not factor in considerations of equity. I then go on to evaluate mean equivalent income (MEI) as a combined measure of production and consumption efficiency: MEI values income to large households more than income of small households, as the sharing of consumption goods in large households yields higher utility from a given amount of income (i.e., household consumption display increasing economies of scale). After that, welfare impacts across income quintiles illustrate how impacts are distributed across income and the Atkinson index is used as a measure of distributional fairness for comparing and ranking policy options taking both efficiency and equity into account. While different indices of inequality exist (popular among them are the Lorenz curve (a graphical representation of inequality) and the Gini coefficient), the Atkinson index is a prominent example of an index that allows for the ranking of policy outcomes if the policies have impacts on both equality and social welfare (Subramanian, 2007). The Atkinson index does not readily let itself be interpreted as a measure of inequality but represents the degree of aversion to inequality present in a given situation. The central parameter of inequality aversion of the Atkinson index can be measured empirically and the literature on this subject provides ranges of values that this parameter plausibly may take.

4.1 Mean income

MI is defined as the mean income across the population where all household members are assumed to benefit from household income as if this income where equally distributed among household members:

$$\mathrm{MI} = \frac{\sum_h w_h s_h \frac{Y_0 + EV_h}{s_h}}{\sum_h w_h s_h},$$

where w_h and s_h are statistical weight and size of household h . Y_0 is household income in the BAU scenario and EV_h is equivalent variation: the change in income at BAU prices that would have resulted in the same consumption utility as does the scenario impacts.

This measure of income is a linear transformation of aggregate EV $\sum_h w_h EV_h$ and will rank scenario outcomes that same way a model with one aggregate household would. The ranking reflects the efficiency of the economy in producing the goods that households value. The results therefore are directly comparable with previous studies that employ such aggregate households. In particular, Table 6 shows that the trade-offs between different carbon tax designs look similar as in Landis, Rausch, et al. (2018). Specifically, the differentiation of carbon tax rates on motor and thermal fuels is efficient for early years and less ambitious targets. This is due to considerable pre-existing taxes on motor fuels that distort the initial economy and make additional abatement in the transport sector expensive (Bovenberg and Goulder, 1996; Landis, Rausch, et al. 2018). By 2050, uniform taxation of carbon across fuels and sectors is the most efficient policy (among those evaluated) for both levels of ambition of climate policy.

It merits analyzing changes MI across different recycling schemes in order to see how revenue recycling affects the economy's productivity. The results in Table 6 make it clear that recycling carbon tax revenue through per-capita lump-sum payments (scenarios LS) consistently results

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[9] This is according to a communication by the Federal Office for the Environment (BAFU) from August 2018 to be found at https://www.bafu.admin.ch/co2-abgabe (accessed 9 October 2018).

[10] https://www.bsv.admin.ch/bsv/de/home/sozialversicherungen/ueberblick/beitraege.html

[11] https://www.estv.admin.ch/estv/de/home/mehrwertsteuer/fachinformationen/steuersaetze.html

Table 6 Percentage change of MI from BAU for different years and scenarios

	2035			2050		
	Uniform	**etsDiff**	*etsUni*	**Uniform**	etsDiff	etsUni
15TPC						
LS	− 0.295	− 0.263	− 0.311	− 0.862	− 0.869	− 0.876
LT	− 0.269	− 0.238	− 0.283	− 0.836	− 0.844	− 0.850
VAT	− 0.281	− 0.249	− 0.296	− 0.841	− 0.849	− 0.856
10TPC						
LS	− 0.497	− 0.487	− 0.531	− 1.458	− 1.580	− 1.524
LT	− 0.463	− 0.456	− 0.495	− 1.426	− 1.551	− 1.491
VAT	− 0.483	− 0.473	− 0.517	− 1.438	− 1.561	− 1.504

Note: Choices of recycling schemes and carbon tax design that yield the highest MI are in bold, and choices that yield the lowest MI are in italic font

in the least efficient outcome of the three options in terms of productivity. As consistently, the labor tax reduction (in scenarios LT) looks to produce outcomes where productivity is highest.

To understand what drives the differences between the per-capita lump-sum recycling and the recycling via labor tax reductions, consider that, in my model, labor tax reductions have no direct impact on the efficiency of labor allocation: labor supply is fixed and the wage rate (remuneration of labor before taxation) is determined by the marginal productivity of labor. In the stylized world of my model, therefore, a labor tax reduction is functionally equivalent to a lump-sum payment. Recycling schemes LS and LT only differ by which households are reached by the effective lump-sum payments to what extent. Analyzing to what extent income is made up by labor (Figure 6 in Appendix 1 shows that high-income households earn a bigger part of their income from labor than low income households) and considering that a per-capita payments increase relative income more for low-income households, one sees that LS recycling tends to increase spending for low-income households while LT recycling increases that of high-income households. Figure 1 shows that its the low-income households that tend to have the more fossil fuel-intensive consumption. By promoting the consumption of households that demand relatively more fossil fuels, the LS recycling thus creates additional pressure on the production sector to abate emissions and thus decreases the productive efficiency of the economy relative to the LT recycling.

The VAT recycling, finally, distorts consumption choices by not affecting all consumption goods to the same degree and tends to increase the spending power of low-income households more than that of high-income ones (see Figure 5 in Appendix 1). Both effects point toward low efficiency, but the model results show that the overall effect is still better than under LS recycling.

4.2 Mean equivalent income

The definition of MEI

$$\mathrm{MEI} = \frac{\sum_h w_h s_h \frac{Y_0+EV_h}{\sqrt{s_h}}}{\sum_h w_h s_h}$$

uses the same weighting of average household values as MI but takes the mean of household *equivalent* income which takes economies of scale in consumption into account: household h's real income $Y_0 + EV_h$ is divided by $\sqrt{s_h}$. This measure thus takes both efficiency of production and efficiency of consumption into account.[12]

Table 7 shows that MEI ranks the three design of carbon taxation the same way as MI. But when looking at the ranking of recycling schemes, it becomes evident that the LS recycling gets an important boost by considering the efficiency of consumption. Under per-capita lump-sum recycling, refunds are given in proportion to the size of the household, which is the same parameter that drives the economies of scale of consumption. At the same time, labor tax reduction tend to reach high-income households with their high shares of wages in overall income. These households tend to be bigger than low-income households, but the relation between refunds and household size is not as direct as in the LS scenarios. The VAT recycling, finally, is worst at allocating refunds to large households: While LT distributed revenue in proportion to labor income (with high-income shares for the larger high-income households) VAT recycling gives comparably more to (on average smaller) low-income households with their bigger fossil fuel expenditure.

It should be noted that the advantage that the LS recycling has over the LT recycling, while consistent across years, targets, and carbon tax designs, is small. The main conclusion from assessing policy scenarios through the lens of MEI would be that VAT recycling should be avoided.

4.3 Distributional impacts and social welfare

Empirical evidence suggests that consumers value a given amount of additional income more if they are in a situation when their income is low than if it is high (see, e.g., (Layard et al., 2008) and references therein). Other results point to the fact that in a societal context, people display some inequality aversion and prefer outcomes where wealth is more equally distributed (Carlsson et al., 2005; Fehr and Schmidt, 1999).

My results indicate that different revenue recycling methods result in different distributions of policy cost

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[12] Between households with the same expenditure structure, MEI would find it efficient to allocate all income from small households to that of large households, as these generate more equivalent income from nominal income than do small ones. It is only by introducing inequality aversion in the social welfare function that a trade-off between efficient consumption by large households and the aversion of starving small households from income can be made.

Table 7 Percentage change of MEI from BAU for different years and scenarios

	2035			2050		
	uniform	**etsDiff**	*etsUni*	**uniform**	etsDiff	etsUni
15TPC						
LS	− 0.269	− 0.236	− 0.282	− 0.831	− 0.835	− 0.843
LT	− 0.271	− 0.237	− 0.283	− 0.833	− 0.836	− 0.845
VAT	− 0.291	− 0.255	− 0.305	− 0.846	− 0.848	− 0.858
10TPC						
LS	− 0.458	− 0.446	− 0.487	− 1.415	− 1.534	− 1.476
LT	− 0.460	− 0.447	− 0.489	− 1.416	− 1.535	− 1.478
VAT	− 0.489	− 0.474	− 0.522	− 1.438	− 1.554	− 1.500

Note: Choices of recycling schemes and carbon tax design that yield the highest MEI are in bold, and choices that yield the lowest MEI are in italic font

among households of different income quintiles. Figures 2 and 3 illustrate this for the scenarios 15TPC and 10TPC and the years 2035 and 2050. While the distribution of policy cost is progressive if revenue is returned via a lump-sum per-capita refund, labor tax reductions result in a regressive distribution of policy cost and VAT reductions in an almost neutral but still slightly regressive distribution.

MEI as a measure of average welfare does not consider inequality, but it can be modified it by the Atkinson index A_ε to construct a social welfare function that takes inequality into account (Atkinson, 1970):

$$\mathrm{SW} = \mathrm{MEI} \times (1 - A_\varepsilon),$$

with

$$A_\varepsilon = 1 - \frac{1}{\mathrm{MEI}} \left[\frac{\sum_h w_h s_h \left(\frac{Y_0 + EV_h}{\sqrt{s_h}} \right)^{1-\varepsilon}}{\sum_h w_h s_h} \right]^{\frac{1}{1-\varepsilon}}$$

and where I chose $\varepsilon = 1.25$.[13] Social welfare simplifies to

$$\mathrm{SW} = \left[\frac{\sum_h w_h s_h \left(\frac{Y_0 + EV_h}{\sqrt{s_h}} \right)^{1-\varepsilon}}{\sum_h w_h s_h} \right]^{\frac{1}{1-\varepsilon}}.$$

If I include inequality aversion via an Atkinson index, the ranking of the recycling methods changes (see Table 8). The per-capita lump-sum recycling now yields the best results for all policy scenarios and by a wide margin. Intuitively, per-capita lump-sum recycling helps low-income households the most and thus lowers the Atkinson index, because the index gives the losses or gains of low-income households more weight. The overall results for social welfare in Table 8 and comparison with Table 7 imply that switching from labor tax reduction to lump-sum transfers reduces inequality aversion and thus the Atkinson index.

But including inequality aversion in my analysis not only affects the ranking of revenue recycling schemes but also that of tax design. If tax design is chosen based on MI, the scenarios 15TPC_etsDiff and 10TPC_etsDiff are preferable to the respective uniform tax scenarios in 2035. But based on social welfare, and thus considering inequality aversion, the uniform tax scenarios are always to be preferred if taxes are recycled via per-capita lump-sum transfers. This becomes plausible if one considers that under tax differentiation, a higher burden is placed on taxation of thermal fuels, which is notably regressive on the expenditure side while taxation of motor fuels (which is progressive) is eased (Landis, Rausch, et al. 2018). Comparing the impact on social welfare of carbon tax design choice and recycling scheme choice shows that the latter is the more important.

The parametrization of inequality aversion is not straightforward and different studies have come up with a range of estimates (Layard et al., 2008). In order to account for uncertainty about the correct value of inequality aversion to employ in evaluation of social welfare, I report social welfare results for alternative choices of ε for computing the Atkinson index in Appendix 2. Reflecting lower and upper bound estimates of inequality aversion in subgroups of the sample surveyed by Layard et al. (2008), I choose $\varepsilon = 0.85$ and $\varepsilon = 1.85$ as lower and upper bound estimates of inequality aversion. For both choices, uniform carbon taxation with per-capita lump-sum transfers remains the best policy option across years 2035 and 2050 and targets 15TPC and 10TPC.

5 Conclusions

This paper analyses different policy options for reaching Switzerland's climate targets for 2050. It considers different versions of carbon pricing and different schemes for returning carbon tax revenue back to households. The results are analyzed both in terms of economic efficiency by looking at mean real income of Swiss residents and in terms of equity by comparing outcomes across scenarios in terms of a social welfare function that values financial gains by low-income households more than the same gains by high-income households.

I find that the differentiation of carbon tax rates between motor fuels and thermal fuels, while beneficial in terms of production efficiency, are not favored if consumption efficiency and inequality aversion are factored in. I find this conclusion to be stable across the range of plausible degrees of inequality aversion.

When I compare different recycling schemes, I find that (i) the choice of recycling scheme has the larger influence on social welfare (considering inequality aversion) than does the choice of carbon taxing framework and (ii) that there is an efficiency-equity trade-off in choosing the revenue recycling scheme and that the equity concerns

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[13] This is very close to the central estimate found by (Layard et al., 2008) and similar to the upper value used by (Creedy and Sleeman, 2006).

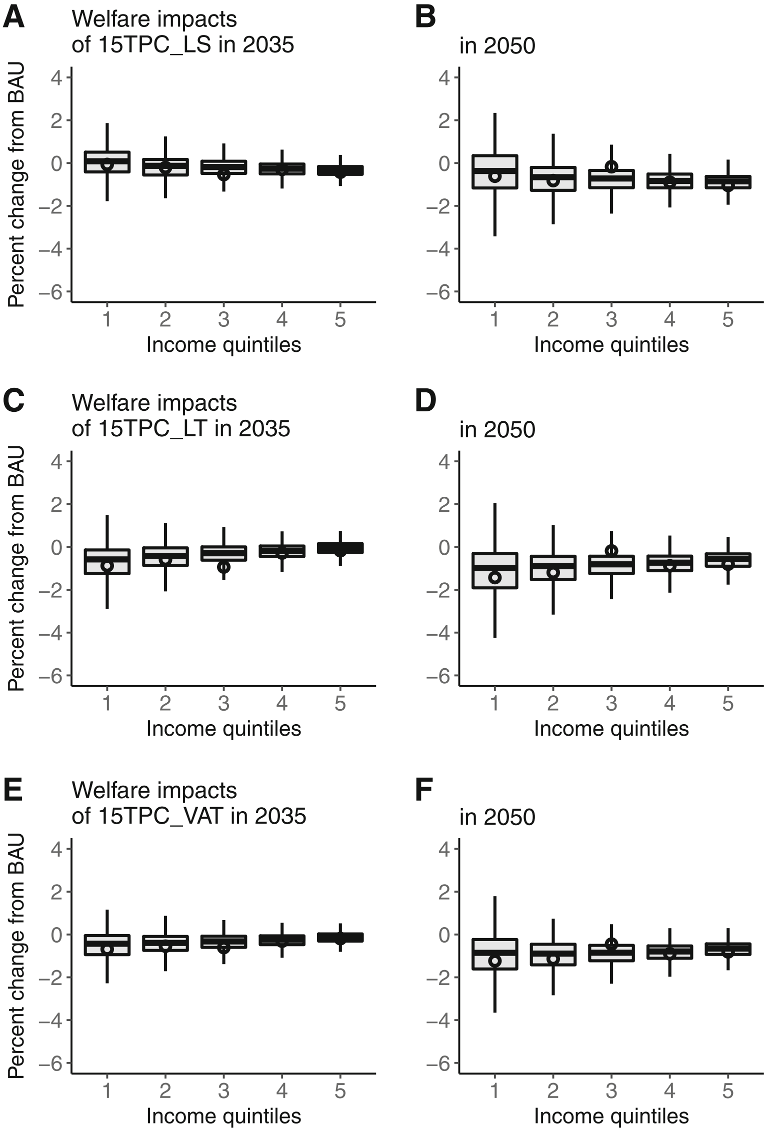

Fig. 2 Distribution of welfare impacts across income quintiles for different revenue recycling schemes (15TPC target) in 2035 (**a**, **c**, and **e**) and 2050 (**b**, **d**, and **f**)

drive the decision. With the currently implemented per-capita lump-sum transfers for recycling the tax revenue, climate policy costs low-income households less than it does high-income households. This effect would be less pronounced or even reversed if the revenue were recycled via reductions in labor taxation or VAT taxes on necessary goods. Assuming a social welfare function that incorporates inequality aversion and thus values decreased losses by members of low-income households more than the increased losses by members of high-income households, I find that per-capita lump-sum revenue recycling is the best of the considered choices. The textbook argument for focusing on aggregate national income implies that wealth could be redistributed in a lump-sum fashion even from the VAT reduction outcome. But lacking the political means of implementing such transfers, the trade-off between aggregate efficiency and equity persists and the lump-sum transfers (currently implemented in Switzerland) seem to be a reasonable choice.

A shortcoming of my model is that it cannot represent the benefits from labor tax reductions predicted by the literature on the double dividend.[14] This is due to missing information about labor supply decisions on the household level. As revenue recycling in the form of labor tax reductions result in increased inequality, the

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[14] The taxation of labor distorts the leisure-labor decision of households, and reducing this distortion increases aggregate economic efficiency (see, e.g., (Goulder, 1995)).

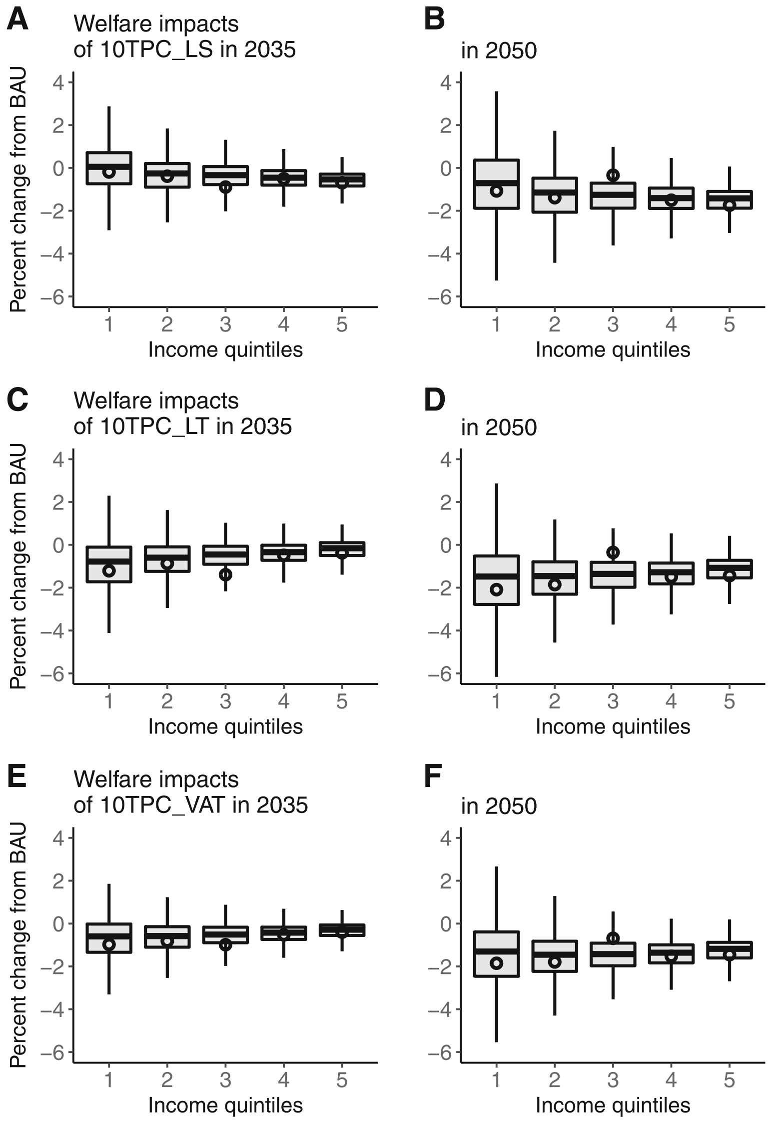

Fig. 3 Distribution of welfare impacts across income quintiles for different revenue recycling schemes (10TPC target) in 2035 (**a**, **c**, and **e**) and 2050 (**b**, **d**, and **f**)

Table 8 Social welfare for different years and scenarios

	2035			2050		
	uniform	etsDiff	etsUni	**uniform**	*etsDiff*	etsUni
15TPC						
LS	− 0.181	− 0.215	− 0.189	− 0.763	− 0.807	− 0.777
LT	− 0.567	− 0.572	− 0.600	− 1.133	− 1.157	− 1.157
VAT	− 0.530	− 0.535	− 0.559	− 1.105	− 1.129	− 1.127
10TPC						
LS	− 0.370	− 0.480	− 0.406	− 1.348	− 1.564	− 1.439
LT	− 0.872	− 1.054	− 0.954	− 1.828	− 2.006	− 1.936
VAT	− 0.813	− 0.902	− 0.878	− 1.792	− 1.966	− 1.895

Note: Choices of recycling schemes and carbon tax design that yield the highest social welfare are in bold, and choices that yield the lowest MEI are in italic font

additional benefits from more efficient labor supply decisions would also have to be traded off against equity concerns.

Also, the model cannot discern cantonal budgets, and due to different income tax rates in different cantons, in reality, revenue neutrality by canton may require different levels of budget balancing, which may have further impacts on the distribution of overall policy cost. In my modeling, I implicitly assume that such differences in budgets of cantons are compensated by inter-cantonal transfers.

Appendix 1: Additional BAU statistics

Figures 4 to 6 show the distribution of income (as by the model), share of expenditures liable to VAT reductions

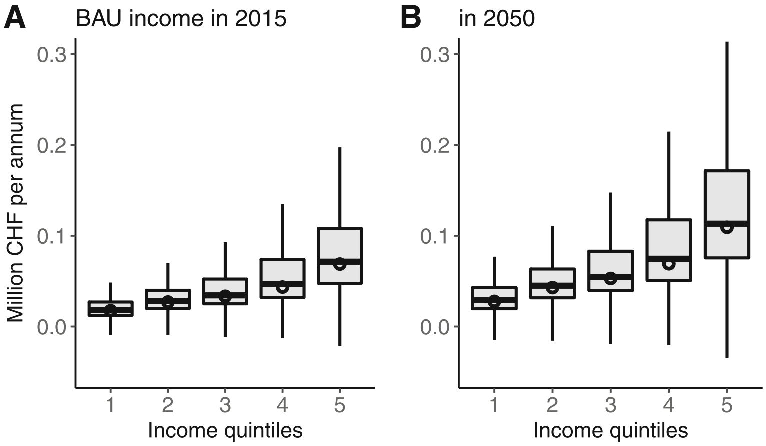

Fig. 4 Distribution of income as measured by the model within and across income quintiles in 2015 (**a**) and in 2050 (**b**). Note: Income quintiles are according to allocation by the statistical office. The circles show mean values

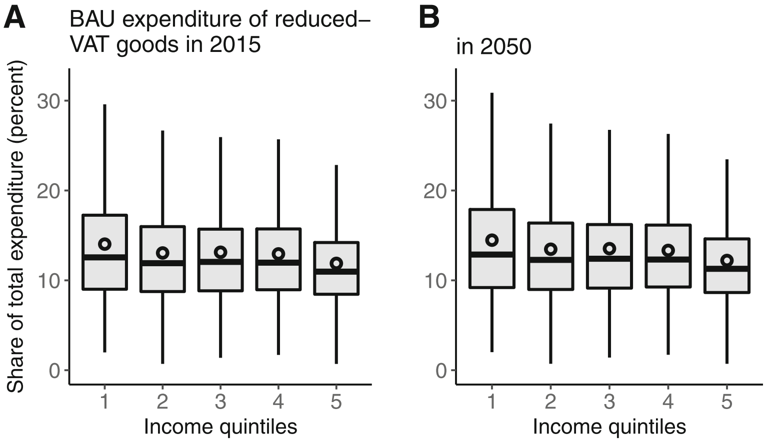

Fig. 5 Distribution of share of expenditures liable to VAT reductions in the VAT-reducing recycling scenarios within and across income quintiles in 2015 (**a**) and in 2050 (**b**). Note: Income quintiles are according to allocation by the statistical office. The circles show mean values

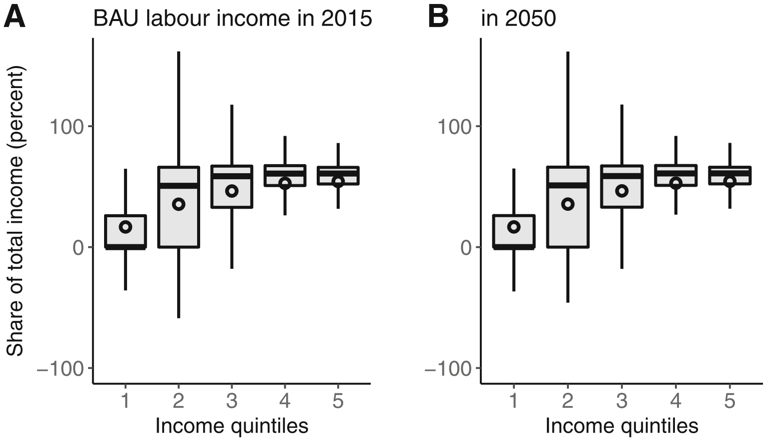

Fig. 6 Distribution of share of labor income in total household income within and across income quintiles in 2015 (**a**) and in 2050 (**b**). Note: Income quintiles are according to allocation by the statistical office. The circles show mean values

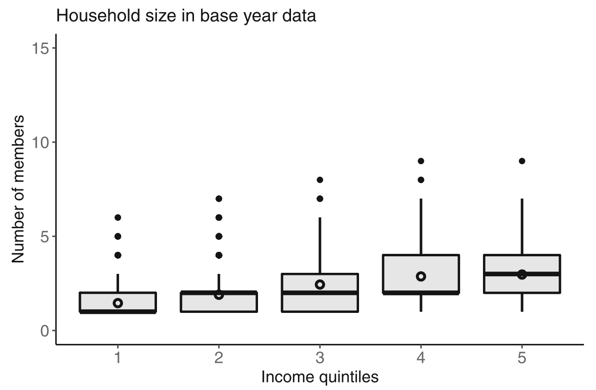

Fig. 7 Distribution of household size within and across income quintiles. Note: Income quintiles are according to allocation by the statistical office. The circles show mean values

in the respective scenarios, and share of labor income in total income within and across income quintiles. Note that in the base year situation, I calibrate the model to 63 households display negative income due to net transfer payments that exceed taxed labor and capital income (their consumption budget is still positive due to dissaving). In the BAU, this number remains 63 and increases to 64 for some policy scenarios. These negative incomes are reflected by the whiskers of the box plots Figs. 4 and 6 reaching below 0 (labor income is always positive, and its share in negative income was reported as negative).

Figure 7 shows household size across income quintiles. It can be seen that households in upper income deciles tend to be larger.

Appendix 2: Sensitivity analysis with respect to inequality aversion

This section of the Appendix displays results for social welfare if alternative parameters for the inequality aversion are assumed. Table 9 shows the results for the inequality aversion parameter $\varepsilon = 0.85$ and Table 10 for $\varepsilon = 1.85$.

It should be noted that in the case of $\varepsilon = 1.85$, welfare results start to become remarkably sensitive to outcomes for very low-income households. My model predicts negative income for about 65 households (depending on the scenario). Ignoring those households for evaluating the Atkinson index yields the numbers presented in this publication. I feel that I can safely ignore these households as outliers as they constitute a small fraction of the modeled households, and the unexpected behavior of their income is due to unconvincing initial data as far as I can tell (unconvincing here means that I find data points unlikely to represent the situation of real households over a longer period of time).

Table 9 Social welfare for different years and scenarios ($\varepsilon = 0.85$)

	2035			2050		
	Uniform	etsDiff	etsUni	**Uniform**	etsDiff	etsUni
15TPC						
LS	− **0.196**	− 0.197	− 0.202	− 0.768	− 0.795	− 0.779
LT	− 0.411	− 0.393	− 0.430	− 0.975	− 0.990	− 0.991
VAT	− 0.406	− 0.389	− 0.426	− 0.967	− 0.982	− 0.982
10TPC						
LS	− **0.364**	− 0.401	− 0.387	− 1.331	− 1.500	− 1.400
LT	− 0.637	− 0.661	− 0.680	− 1.592	− 1.738	− 1.665
VAT	− 0.634	− 0.651	− 0.676	− 1.586	− 1.731	− 1.659

Note: Choices of recycling schemes and carbon tax design that yield the highest social welfare are in bold, and choices that yield the lowest social welfare are in italic font

Appendix 3: Model description

Computational strategy

Following Mathiesen (1985) and Rutherford (1995), I formulate the model as a mixed complementarity problem and represent the economic equilibrium through three classes of conditions: zero profit, market clearance, and budget balance. Model formulation is automated through the Mathematical Programming System for General Equilibrium Analysis (MPS/GE) (Rutherford, 1999) in GAMS, and the internally formulated model is solved using the PATH solver (Dirkse and Ferris, 1995). The calibration of the numerical model follows the standard procedure in applied general equilibrium modeling (see, for example, Böhringer et al., 2018 and Harrison et al., 1997).

To overcome dimensionality restrictions, I employ a sequential recalibration algorithm as employed by Rutherford and Tarr (2008). The algorithm decomposes the large-scale market equilibrium problem into two subproblems and iterates until a consistent equilibrium solution is found. The first subproblem solves a representative agent version by replacing the heterogeneous households by a single representative agent (RA). The second subproblem

Table 10 Social welfare for different years and scenarios ($\varepsilon = 1.85$)

	2035			2050		
	uniform	*etsDiff*	etsUni	**uniform**	etsDiff	etsUni
15TPC						
LS	− 0.311	− 0.535	− 0.365	− 0.806	− 0.894	− 0.839
LT	− 1.337	− 1.562	− 1.474	− 1.786	− 1.813	− 1.850
VAT	− 1.097	− 1.294	− 1.193	− 1.679	− 1.711	− 1.736
10TPC						
LS	− 0.838	− 1.878	− 1.094	− 1.617	− 2.021	− 1.890
LT	− 2.358	− 8.516	− 2.956	− 3.037	− 3.381	− 3.539
VAT	− 1.793	− 2.985	− 2.074	− 2.838	− 3.109	− 3.290

Note: Choices of recycling schemes and carbon tax design that yield the highest social welfare are in bold, and choices that yield the lowest social welfare are in italic font solves a partial equilibrium relaxation of the household side by evaluating household demand functions taking equilibrium prices from the first subproblem as given. In a next iteration, the utility function of the RA in the first subproblem is recalibrated to the observed aggregate demands of the second subproblem. Solution of the first and then the second subproblem and recalibration of the first subproblem is iterated until the to subproblems have converged.[15]

Nesting structure of consumption and production

See Figure 8 and Table 11.

Adjustments between household data and national accounts

See Table 12.

Algebraic description of the model

We formulate the model as a system of nonlinear inequalities and characterize the economic equilibrium as a mixed complementary problem (MCP) (Mathiesen, 1985 and Rutherford, 1995)[16] consisting of two classes of conditions: zero profit and market clearance. Zero-profit conditions exhibit complementarity with respect to activity variables (quantities), and market clearance conditions exhibit complementarity with respect to price variables. We use the ⊥ operate to

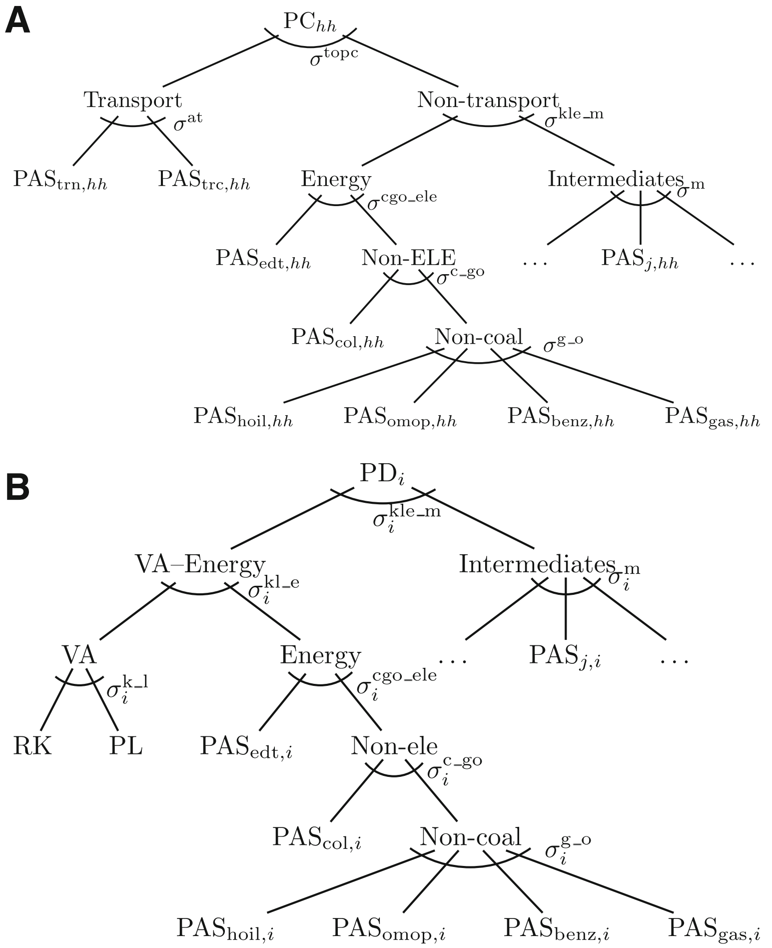

Fig. 8 Nesting of constant-elasticity-of-substitution (CES) functions in production and consumption. *Notes:* Intermediate demand by sector *i* of good *j* is bought on Swiss markets at prices $PAS_{j,i}$. The costs for labor and capital are reflected by *PL* and *PK*. Sectoral output is prices PD_i. $PAS_{i,hh}$ are the prices of commodities i purchased on national markets by households. **a** Consumption. **b** Production

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[15] See (Rausch et al., 2011, pp. 3–7) for a more elaborated description of the decomposition algorithm.

[16] A characteristic of many economic models is that they can be cast as a complementary problem. Mathiesen (1985) and Rutherford (1995) have shown that a complementary-based approach is convenient, robust, and efficient. The complementarity format embodies weak inequalities and complementary slackness, relevant features for models that are not integrable and contain bounds on specific variables, for example, activity levels which cannot a priori be assumed to operate at positive intensity. Such features are not easily handled with alternative solution methods.

Table 11 Elasticities of substitution in utility and production functions and trade

	Up to 2020	2035	2050
Consumption			
σ^{topc}	0.5	0.5	0.5
σ^{at}	0.5	0.9	1.5
σ^{kle_m}	0.5	0.9	1.5
σ^{cgo_ele}	0.51	0.918	1.53
σ^{c_go}	0.15	0.15	0.15
σ^{g_o}	0.75	0.75	0.75
σ^{m}	0.5	0.9	1.5
Production			
$\sigma_i^{kle\_m}$	0.47–0.5	0.846–0.9	1.41–1.5
$\sigma_i^{kl\_e}$	0.44–0.532	0.85–1.03	1.47–1.77
$\sigma_i^{k\_l}$	0.48–0.62	0.48–0.62	0.48–0.62
$\sigma_i^{cgo\_ele}$	0.51	0.918	1.53
$\sigma_i^{c\_go}$	0.15	0.15	0.15
$\sigma_i^{g\_o}$	0.75	0.75	0.75
σ_i^{m}	0.25	0.45	0.75
Trade			
σ_i^{A}	0.5–2	0.5–2	0.5–2
σ_i^{T}	0.4–2	0.4–2	0.4–2

indicate complementarity between equilibrium conditions and variables. Model variables and parameters are defined in Tables 13, 14, and 15. We formulate the problem in GAMS and use the mathematical programming system MPSGE (Rutherford, 1999) and the PATH solver (Dirkse and Ferris, 1995) to solve for non-negative prices and quantities.

Zero-profit conditions

The zero-profit conditions for activities listed in Table 14 are given in Eqs. (1)–(18) on the next page.[17] The complementarity program ensures that, at a numerical solution, activities either make zero economic profits or have bigger unit costs than revenues and are thus not active.

Equations (1)–(3) include the activities that transform market goods (priced at $PS_{st,c}$ and $PATS_{i,c}$) into (aggregate) household welfare (priced at PW_c). Equation 2 shows how cost of generating commodities g relate to their sale prices on the domestic market PD_g and on the world market PFX. Differentiating their output between supply to the domestic and supply to export market, the different industries face the constant-elasticity-of-transformation functions

$$r_g^{YX} := \left[\theta_{D,g}^{YX}\left(PD_g\right)^{1+\sigma_g^T} + \left(1-\theta_{D,g}^{YX}\right)(PFX)^{1+\sigma_g^T}\right]^{\frac{1}{1+\sigma_g^T}}.$$

This differentiation on the output side is only made for traded commodities and the local commodities "household consumption," "government consumption," and "investment demand" ($g \in \{\text{hh}, \text{inv}, \text{govt}\}$) are not exported ($\theta_g^D = 1$).

The unit cost function in (3) for the aggregate consumption basket is[18]

$$c_c^Y := \left[\theta_{ta,c}^{topc}\left(c_c^{ta}\right)^{0.5} + \left(1-\theta_{ta,c}^{topc}\right)\left(c_c^{kle\_m}\right)^{0.5}\right]^2 \qquad \forall c \in C,$$

where

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[17] In the equations, c^{ACT} denote the cost function of activities ACT and r^{ACT} their revenue functions.

[18] This model description adheres to the following conventions of notation. $\theta_{SI,oi}^{NI}$ denotes the value share of good or subnest SI in nest NI of a nested cost function at benchmark prices. Thus, shares of all goods and subnests in any given nest add up to 1. Benchmark levels of price variables P are denoted by parameters $\overline{p}$.

$$c_c^{ta} := \left[\sum_{j \in \{\text{atp,trc}\}} \theta_{j,c}^{ta} \left(\frac{PATS_{j,c}}{\overline{pats}_{j,c}} \right)^{1-\sigma_c^{ta}} \right]^{\frac{1}{1-\sigma_c^{ta}}}$$

$$c_c^{kle\_m} := \left[\theta_{m,c}^{kle\_m} \left(c_c^{m} \right)^{1-\sigma_c^{kle\_m}} + \left(1 - \theta_{m,c}^{kle\_m} \right) \left(c_c^{cgo\_ele} \right)^{1-\sigma_c^{kle\_m}} \right]^{\frac{1}{1-\sigma_c^{kle\_m}}}$$

$$c_c^{m} := \left[\sum_{j \in mat} \theta_{j,c}^{m} \left(\frac{PATS_{j,c}}{\overline{pats}_{j,c}} \right)^{1-\sigma_c^{m}} \right]^{\frac{1}{1-\sigma_c^{m}}}$$

$$c_c^{cgo\_ele} := \left[\theta_{\text{edt},c}^{cgo\_ele} \left(\frac{PATS_{\text{edt},c}}{\overline{pats}_{\text{edt},c}} \right)^{1-\sigma_c^{cgo\_ele}} + \left(1 - \theta_{\text{edt},c}^{cgo\_ele} \right) \left(c_c^{c\_go} \right)^{1-\sigma_c^{cgo\_ele}} \right]^{\frac{1}{1-\sigma_c^{cgo\_ele}}}$$

$$c_c^{c\_go} := \left[\theta_{\text{coa},c}^{c\_go} \left(\frac{PATS_{\text{coa},c}}{\overline{pats}_{\text{coa},c}} \right)^{1-\sigma_c^{c\_go}} + \left(1 - \theta_{\text{coa},c}^{c\_go} \right) \left(c_c^{g\_o} \right)^{1-\sigma_c^{c\_go}} \right]^{\frac{1}{1-\sigma_c^{c\_go}}}$$

$$c_c^{g\_o} := \left[\sum_{j \in \{\text{hoil,omop,gas,benz}\}} \theta_{j,c}^{g\_o} \left(\frac{PATS_{j,c}}{\overline{pats}_{j,c}} \right)^{1-\sigma_c^{g\_o}} \right]^{\frac{1}{1-\sigma_c^{g\_o}}} .$$

$$PD_c \geq PW_c \qquad \perp \quad W_c \geq 0 \qquad \forall c \tag{1}$$

$$P_g \geq r_g^{YX}(PD_g, PFX) \qquad \perp \quad YX_g \geq 0 \qquad \forall g \tag{2}$$

$$c_c^{Y}(PATS_{i,c}) \geq P_c \qquad \perp \quad Y_c \geq 0 \qquad \forall c \in C \tag{3}$$

$$\begin{aligned} & c_{i,g}^{AS}(PA_i, PEDT, PCO2^{(ETS)}, PMOT, REC^{\text{VAT}}) \\ & \quad \geq PATS_{i,g} \qquad \perp \quad AS_{i,g} \geq 0 \qquad \forall i, g \end{aligned} \tag{4}$$

$$\begin{aligned} & c_i^{A}(PD_i, PM_i) \\ & \quad \geq PA_i \qquad \perp \quad A_i \geq 0 \qquad \forall i \end{aligned} \tag{5}$$

$$PFX \geq PM_i \qquad \perp \quad M_i \geq 0 \qquad \forall i \tag{6}$$

$$\begin{aligned} & c_g^{Y}(PFD_{f,g}, PATS_{i,g}) \\ & \quad \geq P_g \qquad \perp \quad Y_g \geq 0 \\ & \qquad \forall g \in G \setminus (C \cup ele) \end{aligned} \tag{7}$$

$$PL \geq PFD_{\text{lab},i}(1 - REC^{WETS}) \qquad \perp \quad LD_i \geq 0 \qquad \forall i \in ets \tag{8}$$

$$\begin{aligned} & PL \geq PFD_{\text{lab},i}(1 - REC^{W}) \qquad \perp \quad LD_i \geq 0 \\ & \qquad \forall i \in I \setminus ets \end{aligned} \tag{9}$$

$$PLS_c \geq PL \left(1 - \frac{REC^{\text{LT}}}{1 + rtfhh_{\text{lab,hh}}} \right) \qquad \perp \quad LS_c \geq 0 \qquad \forall c \tag{10}$$

$$RK \geq PFD_{\mathrm{cap},i} \quad \perp \quad KD_i \geq 0 \quad \forall i \tag{11}$$

$$RKS_c \geq RK \quad \perp \quad KS_c \geq 0 \quad \forall c \tag{12}$$

$$PFX \geq RK \quad \perp \quad KM \geq 0 \tag{13}$$

$$RK \geq PFX \quad \perp \quad KX \geq 0 \tag{14}$$

$$\begin{aligned} & c^{ETEC}_{tec}\left(PATE_{i,tec}, RKE_{tec}, PFD_{\mathrm{lab,ele}}\right) && \qquad (15) \\ & \quad \geq P_{\mathrm{ele}} \quad \perp \quad ETEC_{tec} \geq 0 \quad \forall tec && \end{aligned}$$

$$\begin{aligned} & c^{ASE}_{i,tec}\left(PA_i, PEDT, PCO2^{ETS}, PMOT, PFX\right) && \qquad (16) \\ & \quad \geq PATE_{i,tec} \quad \perp \quad ASE_{i,tec} \geq 0 \quad \forall i, tec && \end{aligned}$$

$$RKES_{tec,c} \geq RKE_{tec} \quad \perp \quad KES_{tec,c} \geq 0 \quad \forall tec, c \tag{17}$$

$$\begin{aligned} PINC_c \geq\ & \theta^{INC}_{L,c} PLS_c && \qquad (18) \\ & + \theta^{INC}_{K,c} RKS_c && \\ & + \theta^{INC}_{KE,tec,c} RKES_{tec,c} && \qquad (19) \\ & + \theta^{INC}_{T,c} P_c \quad \perp \quad NCM_c \geq 0 \quad \forall c. && \end{aligned}$$

The commodity prices $PATS_{i,g}$ faced by consumers are local market prices PA_i plus taxes. Taxes include ad valorem tax rates according to the SAM ($rtva_{i,g}$ and $rtoth_{i,g}$) on the one hand and mineral oil taxes $MOT_{i,g}$, CO_2 taxes $PCO2$ and energy taxes $PEDT$ on physical quantities on the other. Thus, cost function c^{AS} in Eq. 4 is

$$\begin{aligned} c^{AS}_{i,g} :=& \frac{1 + rtva_{i,g} + rtoth_{i,g} - REC^{\mathrm{VAT}}}{1 + rtva_{i,g} + rtoth_{i,g} + rtmot_{i,g}} PA_i \\ & + \phi^{CO2}_{i,g} mult_i \cdot PCO2 + \phi^{EDT}_{i,g} PEDT + \phi^{MOT}_{i,g} PMOT \qquad \forall i \in I, g \in nets \\ c^{AS}_{i,g} :=& \frac{1 + rtva_{i,g} + rtoth_{i,g} - REC^{\mathrm{VAT}}}{1 + rtva_{i,g} + rtoth_{i,g} + rtmot_{i,g}} PA_i \\ & + \phi^{CO2}_{i,g} PCO2^{ETS} + \phi^{EDT}_{i,g} PEDT + \phi^{MOT}_{i,g} PMOT \qquad \forall i \in I, g \in ets, \end{aligned}$$

where $mult_i \cdot PCO_2$ and $PCO2^{ETS}$ are the costs of emitting CO_2 outside and inside the ETS in CHF/tCO_2 and $PEDT$ is the energy tax in CHF/PJ. $\phi^{CO2}_{i,g}$ is the carbon content of commodity i purchased by agent g in tCO_2/CHF and $\phi^{EDT}_{i,g}$ is the energy content in PJ/MCHF. $\phi^{MOT}_{i,g}$ is the amount of mineral oil tax due per value of AS.

The goods i on domestic markets are composed of domestically produced varieties and imported varieties of goods i. The trade-off between the two is modeled as a CES production function according to the Armington assumption and the domestic market price is determined according to the cost function

$$c^A_i := \left[\theta^A_{D,i} \left(PD_i\right)^{1-\sigma^A} + \left(1 - \theta^A_{D,i}\right) \left(PFX\right)^{1-\sigma^A}\right]^{\frac{1}{1-\sigma^A}}$$

in Eq. 5. (6) describes how the price PM_i of imports depends on the exchange rate PFX.

Domestic production of industrial output in Eq. 7 faces the cost function

$$c_g^Y \quad := \quad \left[\theta^{kle\_m}_{kl\_e,g}\left(c_g^{kl\_e}\right)^{1-\sigma_g^{kle\_m}} + \left(1-\theta^{kle\_m}_{kl\_e,g}\right)\left(c_g^{m}\right)^{1-\sigma_g^{kle\_m}}\right]^{\frac{1}{1-\sigma_g^{kle\_m}}} \qquad \forall g \in G \setminus (C \cup ele),$$

where

$$c_g^m := \left[\sum_{j\in mat}\theta^{m}_{j,g}\left(\frac{PATS_{j,g}}{\overline{pats}_{j,g}}\right)^{1-\sigma_g^{m}}\right]^{\frac{1}{1-\sigma_g^{m}}}$$

$$c_g^{kl\_e} := \left[\theta^{kl\_e}_{k\_l,g}\left(c_g^{k\_l}\right)^{1-\sigma_g^{kl\_e}} + \left(1-\theta^{kl\_e}_{k\_l,g}\right)\left(c_g^{cgo\_ele}\right)^{1-\sigma_g^{kl\_e}}\right]^{\frac{1}{1-\sigma_g^{kl\_e}}}$$

$$c_g^{k\_l} := \left[\sum_{f\in F}\theta^{k\_l}_{f,g}\left(\frac{(1+rtf_{f,g})PFD_{f,g}}{\overline{pfd}_{f,g}}\right)^{1-\sigma_g^{k\_l}}\right]^{\frac{1}{1-\sigma_g^{k\_l}}}$$

$$c_g^{cgo\_ele} := \left[\theta^{cgo\_ele}_{\mathrm{edt},g}\left(\frac{PATS_{\mathrm{edt},g}}{\overline{pats}_{\mathrm{edt},g}}\right)^{1-\sigma_g^{cgo\_ele}} + \left(1-\theta^{cgo\_ele}_{\mathrm{edt},g}\right)\left(c_g^{c\_go}\right)^{1-\sigma_g^{cgo\_ele}}\right]^{\frac{1}{1-\sigma_g^{cgo\_ele}}}$$

$$c_g^{c\_go} := \left[\theta^{c\_go}_{\mathrm{coa},g}\left(\frac{PATS_{\mathrm{coa},g}}{\overline{pats}_{\mathrm{coa},g}}\right)^{1-\sigma_g^{c\_go}} + \left(1-\theta^{c\_go}_{\mathrm{coa},g}\right)\left(c_g^{g\_o}\right)^{1-\sigma_g^{c\_go}}\right]^{\frac{1}{1-\sigma_g^{c\_go}}}$$

$$c_g^{g\_o} := \left[\sum_{j\in\{\mathrm{hoil,omop,gas,benz}\}}\theta^{g\_o}_{j,g}\left(\frac{PATS_{j,g}}{\overline{pats}_{j,g}}\right)^{1-\sigma_g^{g\_o}}\right]^{\frac{1}{1-\sigma_g^{g\_o}}}.$$

Besides intermediate inputs prices at $PATS_{i,g}$ production sectors require labor and capital services priced at $PFD_{f,i}$. Equations 8–(12) describe how these prices are derived from net wages PLS_c and net capital rents RK_c received by consumers. General purpose capital services can be traded across international borders and thus, capital rents are determined by the exchange rate PFX as in (13) and (14).

Electricity, finally, is produced using different technologies tec. Their cost function in Eq. 15 is given by

$$c_{tec}^{ETEC} := \left[\theta^{ELE}_{K,tec}\left(RKE_{tec}\right)^{1-\sigma^{ELE}_{tec}} + \left(1-\theta^{ELE}_{K,tec}\right)\left(c^{OM}_{tec}\right)^{1-\sigma^{ELE}_{tec}}\right]^{\frac{1}{1-\sigma^{ELE}_{tec}}} \qquad \forall tec \in T,$$

where

$$c^{OM}_{tec} := \theta^{OM}_{\mathrm{lab},tec}PFD_{\mathrm{lab,ele}} + \sum_i \theta^{OM}_{i,tec}PATE_{i,tec}.$$

Their intermediate inputs are priced at $PATE_{i,tec}$ and this includes market price PA_i plus taxes as given by Eq. 16 and

$$c^{ASE}_{i,tec} := \frac{1+rtva^{e}_{i,tec}+rtoth^{e}_{i,tec}}{1+rtva^{e}_{i,tec}+rtoth^{e}_{i,tec}+rtmot^{e}{}_{i,tec}}PA_i + \phi^{CO2}_{i,tec}PCO2^{ETS} + \phi^{EDT}_{i,tec}PEDT + \phi^{MOT}_{i,tec}PMOT \qquad \forall i \in I, tec \in T \setminus \{\mathrm{fos}\},$$

$$\begin{aligned} c^{ASE}_{i,\mathrm{fos}} := {} & \frac{1 + rtva^{e}_{i,\mathrm{fos}} + rtoth^{e}_{i,\mathrm{fos}}}{1 + rtva^{e}_{i,\mathrm{fos}} + rtoth^{e}_{i,\mathrm{fos}} + rtmot^{e}{}_{i,\mathrm{fos}}} PA_i \\ & + \phi^{CO2}_{i,\mathrm{fos}} \frac{PCO2^{ETS} + PFX \cdot p^{CO2}}{2} + \phi^{EDT}_{i,\mathrm{fos}} PEDT + \phi^{MOT}_{i,\mathrm{fos}} PMOT \qquad \forall i \in I. \end{aligned}$$

The specialized capital services that the power generation technologies require are priced at RKE_{tec} which relates to net capital rents $RKES_{tec,c}$ earned by households as in (17).

A price index of overall net income by consumers is given in Eq. 18.

Market balance equations

$$W_c vom_c \geq \frac{RA_c}{PW_c} \qquad \perp \quad PW_c \geq 0 \qquad \forall c \tag{20}$$

$$YX_c \geq W_c \qquad \perp \quad PD_c \geq 0 \qquad \forall c \tag{21}$$

$$YX_i \frac{\partial c^{XY}_i}{\partial PD_i} \geq A_i \frac{\partial c^{A}_i}{\partial PD_i} \qquad \perp \quad PD_i \geq 0 \qquad \forall i \tag{22}$$

$$YX_{\mathrm{govt}} vom_{\mathrm{govt}} \geq \frac{GOVT}{PD_{\mathrm{govt}}} \qquad \perp \quad PD_{\mathrm{govt}} \geq 0 \tag{23}$$

$$YX_{\mathrm{inv}} vom_{\mathrm{inv}} \geq \sum_c vid_c \qquad \perp \quad PD_{\mathrm{inv}} \geq 0 \tag{24}$$

$$\begin{aligned} vex_i YX_i \frac{\partial r^{XY}_i}{\partial PFX} p^{TRD}_i + KX & \\ \geq {} & vim_i M_i p^{TRD}_i + KM + vb \\ & + vafm^{e}_{i,\mathrm{fos}} ASE_{i,\mathrm{fos}} \frac{\partial c^{ASE}_{i,\mathrm{fos}}}{\partial PFX} \qquad \perp \quad PFX \geq 0 \end{aligned} \tag{25}$$

$$Y_g \geq YX_g \qquad \perp \quad P_g \geq 0 \qquad \forall g \in G \setminus ele \tag{26}$$

$$\sum_{tec} vom^{e}_{tec} ETEC_{tec} \geq vom_{\mathrm{ele}} YX_{\mathrm{ele}} \qquad \perp \quad P_{\mathrm{ele}} \geq 0 \tag{27}$$

$$AS_{i,g} \geq Y_g \frac{\partial c^{Y}_g}{\partial PATS_{i,g}} \qquad \perp \quad PATS_{i,g} \geq 0 \qquad \forall i, g \tag{28}$$

$$\begin{aligned} vam_i A_i \geq {} & \sum_{g \in G \setminus ele} AS_{i,g} \\ & \cdot (vafm_{i,g} - vtax_{i,g}) \\ & + \sum_{tec} ASE_{i,tec} \\ & \cdot (vafm^{e}_{i,tec} - vtax^{e}_{i,tec}) \qquad \perp \quad PA_i \geq 0 \qquad \forall i \end{aligned} \tag{29}$$

$$dedt \cdot MU^{E} \geq \sum_{g \in G \setminus ele} AS_{\mathrm{edt},g} ene_{\mathrm{edt},g} \tag{30}$$

$$+\sum_{tec} ASE_{\mathrm{edt},tec}\, ene^{e}_{\mathrm{edt},tec} \qquad \perp \quad PEDT \geq 0 \qquad \forall e$$

$$etscap \geq \sum_{e,g\in ets} co2_{e,g} AS_{e,g} + \sum_{e,tec} co2^{e}_{e,tec} ASE_{e,tec} - \sum_{e} \frac{co2^{e}_{e,\mathrm{fos}}}{2} ASE_{e,\mathrm{fos}} \qquad \perp \quad PCO2^{ETS} \geq 0 \tag{31}$$

$$cemi \cdot EMICARB \geq \sum_{e,g\in nets} co2_{e,g} AS_{e,g} \qquad \perp \quad PCO2 \geq 0 \tag{32}$$

$$M_i \geq A_i \frac{\partial c^{A}_{i}}{\partial PM_i} \qquad \perp \quad PM_i \geq 0 \qquad \forall i \tag{33}$$

$$LD_i \geq Y_i \frac{\partial c^{Y}_{i}}{\partial PFD_{\mathrm{lab},i}} \qquad \perp \quad PFD_{\mathrm{lab},i} \geq 0 \qquad \forall i \in I \setminus ele \tag{34}$$

$$vfm_{\mathrm{lab,ele}} LD_{\mathrm{ele}} \geq \sum_{tec} vfm^{e}_{\mathrm{lab},tec} \quad ETEC_{tec} \frac{\partial c^{ETEC}_{tec}}{PFD_{\mathrm{lab,ele}}} \tag{35}$$

$$\perp \quad PFD_{\mathrm{lab,ele}} \geq 0 \tag{36}$$

$$KD_i \geq Y_i \frac{\partial c^{Y}_{i}}{\partial PFD_{\mathrm{cap},i}} \qquad \perp \quad PFD_{\mathrm{cap},i} \geq 0 \qquad \forall i \in I \setminus ele \tag{37}$$

$$ASE_{i,tec} \geq ETEC_{tec} \frac{\partial c^{ETEC}}{\partial PATE_{i,tec}} \qquad \perp \quad PATE_{i,tec} \geq 0 \qquad \forall i, tec \tag{38}$$

$$\sum_{c} LS_c\, evom_{\mathrm{lab},c} \geq \sum_{i} LD_i\, vfm_{\mathrm{lab},i} \qquad \perp \quad PL \geq 0 \tag{39}$$

$$1 \geq LS_c \qquad \perp \quad PLS_c \geq 0 \qquad \forall c \tag{40}$$

$$\sum_{c} KS_c\, evom_{\mathrm{cap},c} \geq \sum_{i} KD_i\, vfm_{\mathrm{cap},i} \qquad \perp \quad RK \geq 0 \tag{41}$$

$$1 \geq KS_c \qquad \perp \quad RKS_c \geq 0 \qquad \forall c \tag{42}$$

$$\sum_{c} KES_c\, evom^{e}_{tec,c} \geq vfm^{e}_{\mathrm{cap},tec} \quad ETEC_{tec} \frac{\partial c^{ETEC}_{tec}}{\partial RKE_{tec}} \tag{43}$$

$$\perp \quad RKE_{tec} \geq 0 \qquad \forall tec$$

$$1 \geq KSE_{tec,c} \qquad \perp \quad RKES_{tec,c} \geq 0 \qquad \forall tec, c \tag{44}$$

$$1 \geq NCM_c \qquad \perp \quad PINC_c \geq 0 \qquad \forall c \tag{45}$$

$$QMOT \geq \sum_{i,g} AS_{i,g}\, vtmo_{i,g} + \sum_{i,tec} ASE_{i,tec}\, vtmo^{e}_{i,tec} \qquad \perp \quad PMOT \geq 0 \tag{46}$$

Income balance equations

$$\begin{aligned} RA_{\text{hh}} \geq\ & vinc_{\text{hh}}PINC_{\text{hh}} - vid_{\text{hh}}PW_{\text{hh}} + REC^{\text{LS}}PFX && && (47)\\ & - REINVEST \cdot PFX && \perp \quad RA_{\text{hh}} \geq 0 & \\ RA_{\text{reinvest}} \geq\ & vinc_{\text{reinvest}}PINC_{\text{reinvest}} - vid_{\text{reinvest}}PD_{\text{inv}} && && (48)\\ & + REINVEST \cdot PFX && \perp \quad RA_{\text{reinvest}} \geq 0 & \end{aligned}$$

$$\begin{aligned} GOVT \geq\ & (PW_{\text{hh}} - PD_{\text{inv}})vid_{\text{hh}} \\ & - PW_{\text{hh}}(tcorr_{\text{hh}} + trf_{\text{hh}}) - PFX\left(REC^{\text{LS}} + vb\right) \\ & + PEDT \cdot dedt \cdot MU^{E} + PCO2^{ETS} \cdot etscap \\ & + PCO2 \cdot \sum_{e,g \in nets} AS_{i,g}co2_{e,g} \cdot mult_{i} \\ & + REVT \cdot vinc_{\text{hh}} \cdot NCM_{\text{hh}} \\ & + RKE_{tec} \cdot KES_{tec,\text{hh}} \cdot evom^{e}_{tec,\text{hh}} \cdot mrtinctec_{tec,\text{hh}} \\ & + RK \cdot KS_{\text{hh}} \cdot evom_{\text{cap,hh}} \cdot mrtincf_{\text{cap,hh}} \\ & + PLS_{\text{hh}} \cdot LS_{\text{hh}}\left(evom_{\text{lab,hh}} - mvtfinc_{\text{lab,hh}} - vtf_{\text{lab,hh}}\right) \cdot mrtlinc^{net}_{\text{hh}} \\ & + PL \cdot LS_{\text{hh}}evom_{\text{lab,hh}}\left(rtfhh_{\text{lab,hh}} - REC^{\text{LT}}\right) \\ & - REC^{WETS}\sum_{i \in ets} PFD_{\text{lab},i}LD_{i}vfm_{\text{lab},i} - REC^{W}\sum_{i \in nets} PFD_{\text{lab},i}LD_{i}vfm_{\text{lab},i} \\ & + \sum_{i} PM_{i}A_{i}vim_{i} \cdot rti_{i} + PFX\sum_{i} YX_{i}\frac{\partial r^{YX}_{i}}{\partial PFX}vex_{i} \cdot rtavrow_{i} \qquad (49) \\ & + \sum_{i,tec} ASE_{i,tec}PA_{i}\left(vafm^{e}_{i,tec} - vtax^{e}_{i,tec}\right)\left(rtav^{e}_{i,tec} - REC^{\text{VAT}}\right) \\ & + \sum_{i,g} AS_{i,g}PA_{i}(vafm_{i,g} - vtax_{i,g})\left(rtav_{i,g} - REC^{\text{VAT}}\right) \\ & + PFD_{\text{lab,ele}}\sum_{tec} ETEC_{tec}\frac{\partial c^{ETEC}_{tec}}{\partial PFD_{\text{lab,ele}}}vfm^{e}_{\text{lab},tec}rtf^{e}_{\text{lab},tec} \\ & + \sum_{tec} RKE_{tec}ETEC_{tec}\frac{\partial c^{ETEC}_{tec}}{\partial RKE_{tec}}vfm^{e}_{\text{cap},tec}rtf^{e}_{\text{cap},tec} \\ & + \sum_{f,i \in I \setminus ele} PFD_{f,i}Y_{i}\frac{\partial c^{Y}_{i}}{\partial PFD_{f,i}}vfm_{f,i}rtf_{f,i} \\ & + PMOT \cdot QMOT \qquad \perp \quad GOVT \geq 0. \end{aligned}$$

Constraints for auxiliary variables

In order to realistically represent the options in Swiss climate and energy policy, the model contains additional auxiliary variables (see Table 14) and their corresponding constraints.

In several constraints for auxiliary variables, price levels have to be targeted. Some of the price levels are set in relation to the consumer price index *PINDEX* determined by

$$PINDEX \geq P_{\text{hh}} \qquad \perp \quad PINDEX \geq 0.$$

Table 12 Income and expenditure categories aggregated from household survey data compared with national accounts (numbers are in million Swiss Francs)

HABE	Model	HABE	Model	Adjustment factor
Food and non-alcoholic beverages	C01	26,000	30,894	1.19
Alcoholic beverages and tobacco	C02	4172	9926	2.38
Clothing and footwear	C03	9240	11,312	1.22
Housing and energy	C04	58,586	72,790	1.24
Furniture, equipment, and maintenance	C05	11,218	13,651	1.22
Health	C06	10,380	43,510	4.19
Transport	C07	29,156	30,075	1.03
Communications	C08	6990	7771	1.11
Recreation and culture	C09	25,555	21,482	0.84
Restaurants and hotels	C11	21,379	21,718	1.02
Other goods and services	C1012	11,198	34,980	3.12
Social security contributions	Tax on wages	35,017	75,989	2.17
Health insurance: basic coverage	Transfers	19,699	18,186	*0.92*
Taxes	Tax on income	43,585	62,558	1.44
Health insurance: additional coverage	Transfers	5071	4681	*0.92*
Other insurance	Transfers	7500	6924	*0.92*
Fees	Transfers	2855	2636	*0.92*
Donations and gifts	Transfers	6985	6448	*0.92*
Income from employment	Labor	276,119	274,393	0.99
Income from property and letting	Capital	31,127	111,228	3.57
Pensions and social benefits	Transfers	69,626	64,276	*0.92*
Transfers from other households	Transfers	5541	5115	*0.92*
Intermittent income	Transfers	16,686	15,404	*0.92*
Pensions from AHV/IV	Transfers	31,682	29,248	*0.92*
Pensions from pension funds	Transfers	24,643	22,750	*0.92*
Benefits and daily allowances	Transfers	13,301	12,279	*0.92*
Residual	Savings	134,137	59,160	0.44

Note that transfer payments are not further distinguished in the model (and where adjusted using one single adjustment factor in italics)

Table 13 Sets in the CEPE model

Symbol	Description
$i \in I = \{\text{agr, atp, benz, bme, che, cns, coa, cru, edt, elt, est, ewi, fmp, gas, hoil, hwi, mch, med, nme, nuc, omc, omop, pap, pla, trd, veh, wht, ele, man, ser, trc, try}\}$	Industries
$c \in C = \{hh, reinvest\}$	Representative household and reinvestment activity
$g \in G = I \cup C \cup \{\text{govt, inv}\}$	Industries and agents
$f \in F = \{\text{lab, cap}\}$	Production factors
$hh \in HH = \{h1, \ldots, h9734\}$	Households
$ets \in ETS = \{\text{pap, che, pla, nme, bme, fmp, atp, coa, ele, ewi, hwi}\} \subset I$	Industries within the emission trading system (ETS)
$nets \in NETS = I \setminus ets$	Non-ETS Industries
$e \in E = \{\text{benz, edt, omop, hoil, gas, coa}\} \subset I$	Energy goods
$benz = \{\text{benz}\}$	Motor fuels (gasoline and diesel)
$edt = \{\text{edt}\}$	Electricity consumption commodities
$coa = \{\text{coa}\}$	Coal commodities
$lq = \{\text{gas, omop, hoil, benz}\}$	Liquid fuel commodities
$tec \in T = \{\text{ren, nuc, hyd, fos}\}$	Technologies for electricity generation

Table 14 Variables in the CEPE model

Symbol	Description
Activity levels	
Y_g	Creation of industrial output or household utility
YX_g	Transformation of output to domestic supply or exports
A_i	Armington aggregate of domestic supply and imports
$AS_{i,g}$	Market demand of good *i* by sector/consumer *g*
M_i	Imports
W_c	Welfare from consumption
KM	Imports of capital services
KX	Exports of capital services
LD_i	Labor demand by industry *i*
LS_c	Labor supply by aggregate household
KD_i	Demand for capital services by industry *i*
KS_c	Supply of capital services by aggregate household
$ASE_{i,tec}$	Market demand of good *i* by technology *tec*
$KES_{tec,c}$	Supply of technology-specific capital services by household
$ETEC_{tec}$	Electricity generation
NCM_c	Household income
Commodity prices	
PW_c	Price of household utility
P_g	Price of activity *g*
PD_g	Price of domestic supply
PA_i	Price of Armington commodity *i*
$PATE_{i,tec}$	Price of Armington commodity after taxes
$PATS_{i,g}$	Price of Armington commodity after taxes
PM_i	Price of imports of commodity *i*
PFX	Price of foreign exchange
PL	Gross wage rate
PLS_c	Net employee wage rate
RK	Gross rental rate of capital
RKS_c	Net rental rate of capital
RKE_{tec}	Gross rent of tec specific capital
$RKES_{tec,c}$	Net rent of tec specific capital
$PFD_{f,i}$	Price of production factor *f* in industry *i*
$PINC_c$	Price index of household income
$PCO2^{ETS}$	Permit price in the Swiss ETS
$PCO2$	Price of CO_2 emissions from $CO_2$2 tax
$PEDT$	Price of energy from energy taxation in standardized energy services
$PMOT$	Mineral oil tax
Consumers	
RA_c	Representative household
$GOVT$	Government (tax revenue agent)
Auxiliary variables	
$PINDEX$	Consumer price index
$EMICARB$	Emissions outside ETS under CO_2 tax
MU_e^E	Energy demand under tax on energy good *e*
REC^{LS}	Volume of transfers for compensating households for carbon and energy tax
REC^{LT}	Reduction in labor tax rate for compensating households for carbon and energy tax
REC^{VAT}	Reduction in value-added tax rate for compensating households for carbon and energy tax

Table 14 Variables in the CEPE model (*Continued*)

Symbol	Description
REC^{W}	Wage subsidy rate for compensating industries outside the ETS for carbon and energy tax
REC^{WETS}	Wage subsidy rate for compensating industries in ETS for ETS permit expenditures and energy tax
QMOT	Provision of implicit permits that determines mineral oil tax
REINVEST	Budget adjustment for keeping investment constant
REVT	Revenue generating tax on net household income

The CO_2 tax on non-ETS emissions is set endogenously, in order to restrict national emissions according to the overall emission target. The model achieves this by restricting the amount of CO_2 that is allowed to be emitted through the parameter *EMICARB* and lets the market balance for *PCO*2 set the corresponding carbon tax:

$$cbauemi \cdot EMICARB \geq emitarget - etscap \qquad \perp EMICARB \geq 0.$$

In scenarios where all emissions are taxed uniformly, $etscap = 0$.

The tax on electricity is a tax on physical quantities as well and has to be pegged to the national price indexed *PINDEX* by setting the variable MU^{E}:

$$enetax_{\mathrm{edt}} \cdot PINDEX \geq PEDT \qquad \perp \quad MU^{E}_{\mathrm{edt}} \geq 0.$$

In scenarios where revenue from taxing carbon emissions and energy demand of households is recycled through lump-sum payments, the volume of these payments is determined by REC^{LS} by

$$\begin{aligned} REC^{\mathrm{LS}} \cdot PFX \geq & \sum_{i} \left(AS_{i,\mathrm{hh}} \cdot co2_{i,\mathrm{hh}} \cdot PCO2 \cdot mult_{i} \right) \\ & + AS_{\mathrm{edt,hh}} ene_{\mathrm{edt,hh}} PEDT \qquad \perp REC^{\mathrm{LS}} \geq 0. \end{aligned}$$

In scenarios where revenue from taxing carbon emissions and energy demand of households is recycled through lump-sum payments, the volume of these payments is determined by REC^{LT} by

$$\begin{aligned} REC^{\mathrm{LT}} PL \sum_{c} evom_{\mathrm{lab},c} LS_{c} \geq & \sum_{i} \left(AS_{i,\mathrm{hh}} \cdot co2_{i,\mathrm{hh}} \cdot PCO2 \cdot mult_{i} \right) \\ & + AS_{\mathrm{edt,hh}} ene_{\mathrm{edt,hh}} PEDT \qquad \perp \quad REC^{\mathrm{LT}} \geq 0. \end{aligned}$$

In scenarios where revenue from taxing carbon emissions and energy demand of households is recycled through lump-sum payments, the volume of these payments is determined by REC^{VAT} by

$$\begin{aligned} REC^{\mathrm{VAT}} & \sum_{i \in \{\mathrm{agr,trc}\},g} AS_{i,g} PA_{i} (vafm_{i,g} - vtax_{i,g}) \\ & \geq \sum_{i} \left(AS_{i,\mathrm{hh}} \cdot co2_{i,\mathrm{hh}} \cdot PCO2 \cdot mult_{i} \right) \\ & + AS_{\mathrm{edt,hh}} ene_{\mathrm{edt,hh}} PEDT \qquad \perp REC^{\mathrm{VAT}} \geq 0. \end{aligned}$$

Table 15 Model parameters

Symbol	Description
Elasticity of substitution parameters	
σ_i^T	Elasticity of transformation between domestic and export markets
σ_i^A	Domestic-imported composite in domestic market
σ_c^{topc}	Top level (transport-non-transport composite)
σ_c^{at}	Transport composite
$\sigma_g^{kle\_m}$	Value-added-energy-material composite
σ_g^{m}	Material composite
$\sigma_i^{kl\_e}$	Value-added-energy composite
$\sigma_i^{k\_l}$	Value-added composite
$\sigma_g^{cgo\_ele}$	Energy composite
$\sigma_g^{c\_go}$	Fossil fuel composite
$\sigma_g^{g\_o}$	Liquid fuel and gas composite
σ_{tec}^{ELE}	Capital-O&M composite in electricity generation
Input and expenditure shares	
$\theta_{D,i}^{YX}$	Share of supply to domestic market
$\theta_{at,c}^{topc}$	Share of transport nest in total expenditures
$\theta_{kle\_m,c}^{topc}$	Share of value added and energy in total expenditures
$\theta_{j,c}^{at}$	Shares of commodity *j* in public transport cost bundle
$\theta_{m,g}^{kle\_m}$	Share of materials in *kle_m*
$\theta_{j,g}^{m}$	Shares of commodity *j* in material cost bundle
$\theta_{\mathrm{edt},g}^{cgo\_ele}$	Share of electricity in energy bundle
$\theta_{\mathrm{coa},g}^{c\_go}$	Share of coal in fossil fuel bundle
$\theta_{j,g}^{g\_o}$	Share of commodity *j* in liquid fuel bundle
$\theta_{k\_l,i}^{kl\_e}$	Share of value-added cost in value-added/energy composite
$\theta_{f,i}^{k\_l}$	Share of production factor *f* in value-added composite
$\theta_{D,i}^{A}$	Share of market supply from domestic supply
$\theta_{K,tec}^{ELE}$	Share of capital rents in generation costs
$\theta_{L,c}^{INC}$	Value share of wage earnings in income
$\theta_{K,c}^{INC}$	Value share of capital rents in income
$\theta_{KE,tec,c}^{INC}$	Value share of electricity capital rents in income
$\theta_{T,c}^{INC}$	Value share of transfers in income
Baseline variable values	
$\overline{ps_{st,c}}$	Baseline prices of energy services
$\overline{pats_{j,g}}$	Baseline prices of market goods
$\overline{pfd_{f,i}}$	Baseline factor prices
Other parameters	
std_{st}	Standardized energy use per million CHF
p^{CO2}	EU ETS permit price in CHF per tonne CO_2
p_i^{TRD}	World market prices
$rtva_{i,g}$	Value-added tax rate
$rtoth_{i,g}$	Net rate of other taxes
$rtmot_{i,g}$	Baseline ad valorem mineral oil tax rate
$\phi_{i,g}^{CO2}$	CO_2 intensity of commodity value
$\phi_{i,g}^{MOT}$	Mineral oil tax intensity of commodity value

Table 15 Model parameters (*Continued*)

Symbol	Description
$mult_i$	Fuel specific multiplier on CO_2 tax
$\phi_{i,g}^{EDT}$	Electricity intensity of commodity value
$e_{e,st}$	Energy content of good *e*
vom_g	Baseline output of activity *g*
vid_c	Baseline investment demand
vex_i	Baseline exports
vim_i	Baseline imports
$vafm_{i,g}$	Baseline intermediates demand
vam_i	Baseline market supply
$vtax_{i,g}$	Baseline commodity tax payments
$dedt$	Baseline national energy demand
$ene_{e,g}$	Baseline energy demand
$etscap$	Emission cap for Swiss ETS
$co2_{e,g}$	CO_2 content of energy demand by *g*
$cemi$	Baseline non-ETS emissions
$vist_{st,i}$	Baseline supply of intermediates for energy services
$vidst$	Baseline demand for intermediates for energy services
$vfm_{f,i}$	Baseline factor demand
$evom_{f,c}$	Baseline factor endowment
$vinc_c$	Baseline income
$tcorr_{\mathrm{hh}}$	Difference marginal and average income tax rate times income
trf_{hh}	Benchmark transfers
vb	Benchmark balance of trade
$mrtincf_{f,\mathrm{hh}}$	Marginal income tax rate on factor f
$mrtinctec_{tec,\mathrm{hh}}$	Marginal income tax rate on *tec* specific capital
$mvtfinc_{f,\mathrm{hh}}$	Marginal income tax rate times income for factor f
$vtf_{\mathrm{lab,hh}}$	Volume of social security contributions
$mrtlinc_{\mathrm{hh}}^{net}$	Income tax on labor income based on net income
rti_i	Tariff rate on imports
$rtf_{f,i}$	Tax rate on factor demand
$rtf_{f,tec}^{e}$	Tax rate on factor demand by power generation technologies
$rtfhh_{\mathrm{lab,hh}}$	Tax rate labor provision
$rtavrow_i$	VA tax rate on exports
$vtav_{i,g}$	Baseline value of ad valorem taxes
$rtav_{i,g}$	Net rate of ad valorem taxes
$vtmo_{i,g}$	Baseline value of mineral oil taxes
$emitarget$	National target for CO_2 emissions
$cbauemi$	Baseline emissions outside ETS
$co2tax$	Exogenous CO_2 tax
$eletarget$	National target for electricity demand
$enetax_{\mathrm{edt}}$	Tax on electricity
$target_{tec}^{KEV}$	Technology-specific targets for market shares under KEV
$rtmo_{i,g}$	Baseline mineral oil tax rate

Revenue from taxing non-ETS industries is recycled with a subsidy REC^{W} on wage payments:

$$\begin{aligned} REC^{W} & \sum_{g \in G \setminus ets} \left(LD_{g} \cdot vfm_{\mathrm{lab},g} \cdot PFD_{\mathrm{lab},g} \right) \\ & \geq \sum_{i \in I, g \in I \setminus ets} \left(AS_{i,g} \cdot (co2_{i,g} \cdot PCO2 \cdot mult_{i} + ene_{i,g} PEDT) \right) \qquad \perp REC^{W} \geq 0. \end{aligned}$$

The subsidy REC^{WETS} serves the same purpose for levies on ETS industries. It is set accordingly:

$$\begin{aligned} REC^{WETS} & \sum_{g \in ets} \left(LD_{g} \cdot vfm_{\mathrm{lab},g} \cdot PFD_{\mathrm{lab},g} \right) \\ & \geq \sum_{i \in I, g \in (I \cap ets)} \left(AS_{i,g} \cdot (co2_{i,g} \cdot PCO2^{ETS} + ene_{i,g} \cdot PEDT) \right) \\ & + \sum_{i,tec} \left(ASE_{i,tec} (co2^{e}_{i,tec} \cdot PCO2^{ETS} + ene^{e}_{i,tec} \cdot PEDT) \right) \qquad \perp REC^{WETS} \geq 0. \end{aligned}$$

Changes in tax income and price changes make it necessary to adjust government income *GOVT* such that government can afford to purchase the same amounts of goods as in the baseline. This is achieved by taxing/subsidizing households' after tax income at rate *REVT*

$$GOVT \geq PD_{\mathrm{govt}} \cdot vom_{\mathrm{govt}} \qquad \perp \quad REVT \geq -0.999999.$$

Excise tax rates on mineral oil are not ad valorem but tied to physical quantities. The model accounts for this by counting the physical quantities in terms of taxed value and ensuring that the tax rate is indexed by the national price index *PINDEX*:

$$PMOT \geq PINDEX \qquad \perp \quad QMOT \geq 0.$$

The reinvestment of capital rents is done by the agent reinvest who has the budget RA_{reinvest}. In order to operate, this agent demands services from the sector ser. The model fixes this demand by adjusting reinvest's budget through the variable *REINVEST* according to

$$RA_{\mathrm{reinvest}} \geq PW_{\mathrm{reinvest}} \cdot vom_{\mathrm{reinvest}} \qquad \perp REINVEST \geq -\infty.$$

Abbreviations

BAU: Business as usual; CEPE-HH: Name of the numerical model used for this study; CGE: Computable general equilibrium; CH ETS: Swiss Emission Trading System; CO_2: Carbon dioxide; EU ETS: European Emission Trading System; GDP: Gross domestic product; GHG: Greenhouse gas; MEI: Mean equivalent income; MI: Mean income; MPS/GE: Mathematical Programming System for General Equilibrium Analysis; SEMP: Swiss Energy Modelling Platform; VAT: Value-added tax

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Authors' contributions

All modeling work, analysis of the results, and writing specific to this study have been carried out by the author, Florian Landis. The author read and approved the final manuscript.

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Availability of data and materials

The data bases underlying the analysis are provided by the Swiss Statistical Office and are available to researchers upon signing confidentiality agreements. A description of the household budget survey and contacts to its administrators may be found at https://www.bfs.admin.ch/bfs/en/home/statistics/economic-social-situation-population/surveys/hbs.html. Similarly, the input–output tables of Switzerland can be found at https://www.bfs.admin.ch/bfs/de/home/statistiken/volkswirtschaft/input-output.html. The numerical model is documented in the Appendix 3 of this paper.

Competing interests

The author declares that he has no competing interests.

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