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# Differentiated Carbon Prices and the Economic Cost of Decarbonization

By FLORIAN LANDIS, SEBASTIAN RAUSCH, AND MIRJAM KOSCH\*

*Employing a numerical general equilibrium model with multiple fuels, end-use sectors, heterogeneous households, and transport externalities, this paper examines three motives for differentiated carbon pricing in the context of Swiss climate policy: fiscal interactions with the existing tax code, non-CO<sub>2</sub> related transport externalities, and social equity concerns. Interaction effects with mineral oil taxes reduce carbon taxes on motor fuels and transport externalities increase them. We show that the cost-effective overall carbon tax on motor fuels should be lower than the one on thermal fuels. This is found in spite of the fact that pre-existing taxes on motor fuels are well below our estimate of the transport externality per unit of transport fuel consumption. Differentiating taxes in favor of motor fuels yields only slightly more equitable incidence effects among households, suggesting that equity considerations play a minor role when designing differentiated carbon pricing policies.*

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A fundamental tenet of environmental economics concerning the regulation of a uniformly dispersed pollutant such as carbon dioxide (CO<sub>2</sub>) is that the cost of achieving a given emissions reduction is minimized if marginal abatement costs are equalized across all emitters. Market-based instruments like emission taxes (Montgomery, 1972; Baumol and Oates, 1988) or a system of tradable emission permits (Dales, 1968; Montgomery, 1972) operationalize this idea by establishing a uniform price on emissions across all sources. While policy advisors have been embracing this simple rule, several reasons for deviating from uniform carbon price exist. Theoretical arguments include tax interaction with pre-existing taxes, externalities unrelated to CO<sub>2</sub> emissions, international spillover effects (Markusen, 1975; Hoel, 1996), and market power of large open economies (Krutilla, 1991; Rauscher, 1994). The complexity of analytical expressions that describe second-best pricing rules and efficiency costs means, however, that no general results about the magnitude of overall effects can be obtained. In fact, the ambiguity predicted by Lipsey and Lancaster (1956)'s general theory of the second-best suggests that answers are highly context-specific, i.e. the optimal carbon tax differentiation depends on the type and magnitude of externalities and distortions

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for a given economy.

Our analysis uses the example of climate policy in Switzerland to provide an empirical context in which some of the fundamental aspects of differentiated carbon pricing can be illustrated. A common characteristic of proposals for Swiss carbon tax policy (Federal Council, 2015*a,b*; Imhof, 2012) is to differentiate carbon prices by fuel type with motor fuels being taxed at a much smaller rate than non-transport related fuels. Pre-existing taxes on motor fuels have been identified as a reason for carbon tax differentiation in the Swiss context (Imhof, 2012)<sup>1</sup> as well as in the European context (Paltsev et al., 2005*b*; Abrell, 2010). We elaborate on these previous studies by analyzing cost-effective policy designs with optimally differentiated carbon taxes between motor and thermal fuels and by taking into account that pre-existing taxes on motor fuels are an imperfect instrument for reducing the transport externality.

We analyze how the economic rationale for carbon price differentiation is affected by non-climate related externalities. Given our focus on differentiating carbon taxes on thermal and motor fuels, we specifically examine the role of transportation externalities for cost-effective carbon pricing policies. While internalizing transport externalities suggests taxing motor fuels, tax interaction effects make pricing the externality at the full damage-per-fuel use level sub-optimal (Bovenberg and Goulder, 1996).<sup>2</sup> The question of socially optimal carbon tax differentiation thus has to be examined by jointly considering both effects. An additional confounding factor that we consider is that non-climate related transport externalities are proportional to vehicle-distance traveled rather than to fuel use. A tax on motor fuels intended to reduce the transport externality thus induces unnecessarily high investments in fuel-efficiency of vehicles rather than solely a reduction in vehicle use (Parry and Small, 2005).

Moreover, we examine whether and how differentiated carbon tax policies face an efficiency–equity trade-off, focusing on distributional impacts among household income groups. As low-income households spend a large fraction of their income on heating and electricity, higher energy prices due to taxing thermal fuels may lead to regressive outcomes (Metcalf, 1999; Rausch, Metcalf and Reilly, 2011; Fullerton, Heutel and Metcalf, 2012). In contrast, taxing motor fuels is expected to be mildly progressive as expenditure shares on transportation tend to increase with income (Sterner, 2012). Hence, while differentiating carbon taxes between fuels may enhance efficiency due to dampening adverse tax interaction effects, it

<sup>1</sup>Other recent assessments of Swiss climate policy include Bretschger, Ramer and Schwark (2011); Sceia, Thalmann and Vielle (2009); Sceia et al. (2012), which do not explicitly consider differentiated carbon prices. Sceia, Thalmann and Vielle (2009) and Sceia et al. (2012) analyze transportation-specific emission reduction targets and find them to be an inefficient deviation from economy-wide uniform carbon pricing.

<sup>2</sup>Bovenberg and Goulder analyze optimal taxation of a polluting activity in presence of distortionary labor taxes. Their argument applies to our setting if one views the problem of taxing motor fuels more or less than thermal fuels as correcting the pre-existing motor fuel taxes to optimally manage the transport externality in presence of a distortionary CO<sub>2</sub> tax. From a Swiss perspective, the CO<sub>2</sub> tax is distortionary because, presumably, it makes emitters internalize global effects of climatic change of which Switzerland internalizes only a very small fraction.

may amplify unintended distributional outcomes.

To derive our results, we develop a comparative-static multi-sector small open economy numerical general equilibrium model for Switzerland. The model features a detailed representation of energy supply and conversion activities comprising various fuels and secondary energy supply, thus representing a useful framework to examine the economic cost of decarbonization. Household heterogeneity is captured by the spending and income patterns of 14 representative household groups based on income and work status (retired vs. working age). To capture the major tax distortions in the Swiss economy, the model includes payroll taxes, private income taxes, value-added taxes, import tariffs by commodity, sector-specific output taxes and subsidies, and energy-related taxes including mineral oil taxes. Moreover, we explicitly represent the cost from transport-related externalities.

Our analysis provides evidence that uniform emissions pricing may not be optimal. We find that, even though pre-existing taxes on motor fuels are well below our estimate of transport externalities caused per unit of fuel use (1.23 Swiss Francs (CHF) per liter; measured in 2010 real terms), cost-effective CO<sub>2</sub> taxes on motor fuels should be lower than those on thermal fuels. Our findings suggest, however, that the welfare losses from choosing a uniform carbon tax rather than the cost-effective differentiation scheme are not particularly high (and lower than they would be under current proposals for tax differentiation) for reaching overall emissions targets between 50–60% of 1990 levels.

While tax interaction effects due to pre-existing mineral oil taxes imply a differentiation in favor of motor fuels, the cost-effective differentiation of carbon prices for motor and thermal fuels depends, however, strongly on the size of transport externalities. We find that for upper bound estimates of transport externalities (CHF 1.84 per liter of gasoline measured in 2010 real terms), a cost-effective tax policy would yield outcomes close to the uniform case. The reason is that the negative effects on social welfare due to tax interaction effects associated with high taxes on motor fuels are compensated by the benefits due to reducing the transport externality. In contrast, assuming cost estimates for transport externalities at the lower bound (CHF 0.61 per liter of gasoline measured in 2010 real terms), we find that there exists a strong efficiency argument for differentiating carbon taxes. In this case we find that the cost-effective carbon price on motor fuels is 0.1–0.65 times as big as the tax on thermal fuels, depending on policy stringency. The degree of differentiation diminishes with more stringent CO<sub>2</sub> emissions reductions targets as increasingly more abatement is achieved through lowering the use of motor fuels.

Regarding the equity dimension, our results clearly indicate that taxing motor fuels is progressive whereas taxing thermal fuels is regressive over household income groups for both working and retired households. Thus, our analysis suggests that there may exist a trade-off between efficiency and equity, in particular when transport externalities are high (thus favoring low carbon taxes on motor fuels and high ones on thermal fuels). For decarbonization policies which involve a

combination of carbon taxes on both types of fuels, however, we find that cost-effective policy designs do not affect much the household-level incidence relative to the case of uniform emissions pricing. While their impacts are slightly more regressive than the ones of uniform pricing, we find that the magnitude of these effects is rather small. All current proposals of Swiss climate policy foresee a per capita lump-sum refund for recycling carbon tax revenue which results in clearly progressive overall cost incidence of climate policy for all carbon tax schemes considered. Given these quantitative findings, we conclude that, at least in the Swiss context, equity considerations should only play a second-order role for deciding whether to deviate from uniform carbon pricing.

A small but growing literature has used quantitative methods based on numerical general equilibrium models to investigate the efficiency impacts from carbon price differentiation. As expected, these analyses reveal that there is considerable case-to-case variation of conclusions that are drawn. Comparing given schemes for differentiating carbon prices, [Böhringer and Rutherford \(1997\)](#), [Babiker et al. \(2000\)](#), and [Kallbekken \(2005\)](#) find that differentiating the tax rate on a fossil energy carrier across sectors entails efficiency costs rather than benefits. [Böhringer, Lange and Rutherford \(2014\)](#) ask to what extent carbon leakage provides an efficiency argument for differentiated emission prices in favor of emission-intensive and trade-exposed sectors under unilateral climate policy. They find that both the leakage and terms-of-trade motives yield only small efficiency gains compared to uniform emission pricing and thus conclude that in many cases the simple first-best rule of uniform emission pricing remains a practical guideline for unilateral climate policy design. But systematically checking possible ways of differentiating carbon prices across fuels and end-use sectors, [Boeters \(2014\)](#) shows that the cost-effective pattern of carbon prices in unilateral European climate policy is highly differentiated and offers substantial welfare gains relative to uniform pricing (equivalent to a 27% emissions reduction for free).<sup>3</sup> Our paper adds to this literature by analyzing cost-effective carbon tax differentiation in a framework that jointly considers tax interaction effects, transport externalities that are imperfectly addressed by taxes on motor fuels, and considerations about distributional equity. Moreover, we provide an analysis geared to the specific context of Swiss climate policy in which the issue of carbon tax differentiation is seriously considered as a policy option.

The remainder of the paper is organized as follows. Section [I](#) describes our quantitative framework, including data, model structure, and calibration. Section [II](#) presents the design for our computational experiments. Sections [III](#) presents and discusses simulation results for our central case. Section [IV](#) provides additional robustness checks covering a range of empirically plausible specifications for the

<sup>3</sup>[Boeters \(2014\)](#) finds that the most important drivers for carbon price differentiation are market power in export markets and taxes on consumption, intermediate inputs, and domestic outputs. At the same time, he warns that his model views taxes as distortive inefficiencies and shows that his case for carbon price differentiation weakens if his model channels tax revenues on motor fuels to road construction and maintenance and assumes that these have to be provided in proportion to motor fuel consumption.

size of transport externalities. Section V concludes.

## I. Quantitative Framework

This section provides an overview of the numerical general equilibrium framework used for our analysis. We first describe the various underlying data sources and how we combine them for the purpose of model calibration. We then briefly describe the model structure and highlight its key features, including the representation of transport externalities.

### A. Data

This study makes use of a comprehensive data set which combines various data sources. We merge household-level survey data on income and expenditures with national income and product accounts data.

NATIONAL ECONOMIC ACCOUNTS AND ENERGY DATA.—We use data of the Swiss Input-Output (IO) table for the year 2008 (BFS, 2011) in the version by Nathani et al. (2013). The IO-table provides sectoral information on value flows between industries, households and government agents. These value flows quantify for each industry the inputs of intermediate goods and factors to produce final goods. In the case of households and government they define their demand for goods and their income from factors or taxes respectively. Based on the social accounting data, our model includes payroll taxes (“AHV-Beiträge”), private income taxes, value-added taxes, import tariffs by commodity, sector-specific output taxes and subsidies, and energy-related taxes including mineral oil taxes.

The IO data in its original form distinguishes 66 industries and commodity groups and 20 categories for final demand. For the purpose of our study, we reduce the number of industries by aggregating the original IO-table into 22 sectors, which we separately represent in our model. Table 1 provides an overview of our commodity aggregation. We identify nine sectors of energy supply and conversion separating various fuels (motor and heating fuels, natural gas, coal, crude oil) and secondary energy supply (comprising various forms of electricity and heat). The choice of aggregation for the 13 non-energy sectors is guided by the considerations to separately identify sectors which are large in terms of economic size (i.e., value of output), exhibit a high energy-intensity (e.g., transportation), or are subject to the Swiss emissions trading system (ETS). For model calibration, we then use the aggregated value flows of intermediate and final goods as well as tax payments of these 22 sectors. Additionally, we use national accounts data on consumption, taxes and factor income for final demand sectors.

Besides value flows on economic transactions, our version of the IO-table includes physical accounts for energy production and consumption which are consistently linked with economic data in value terms. Furthermore, CO<sub>2</sub> emissions of all energy-related economic activities are derived from these physical quantities. Hence, we have detailed information on CO<sub>2</sub> emissions of industries, household and government agents.

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

Sectors ( $i \in I$ )	
<i>Non-energy</i>	Agriculture (agr), Pulp, paper and paper products* (pap), Chemicals and chemical products* (che), Rubber and plastic products* (pla), Other non-metallic mineral products* (nme), Basic metals* (bme), Fabricated metal products, except machinery and equipment* (fmp), Medical, precision and optical instruments, watches and clocks* (med), Other manufacturing (man), Services (ser), Construction (cns), Transportation (excluding air transportation) (trn), Air transportation* (atp)
<i>Energy supply</i> <i>ℳ conversion</i>	Motor fuels (toi), Heating fuels (oil), 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)
<i>Final demand</i>	Private consumption by 14 representative households, government consumption, investment demand
Electricity generation technologies ( $p \in P$ )	Hydro, Pump hydro storage facilities, Gas, Nuclear, Oil, Solar, Wind, Biomass, Geothermal, Combined heat and power
Household groups ( $h \in H$ )	working-age households grouped by annual income decile with “EH1” (=lowest decile) to “EH10” (=highest decile) Retirees grouped by annual income quartiles with “RH1” (=lowest quartile) to “RH4” (=highest quartile)

*Notes:* \*Indicates sectors which are subject to the Swiss emissions trading system for energy-intensive industries.

MICRO-HOUSEHOLD DATA FROM THE “HABE” SURVEY.—The Swiss Household Budget Survey “Haushaltsbudgeterhebung (HABE)” is a representative survey of the permanent resident population of Swiss households which is conducted on an annual basis by the Swiss Federal Statistical Office (BFS). For each household in the sample it provides detailed information about expenditures for various consumption goods and different types of income (wages, capital rents, or government transfers). Additionally, the HABE data provides detailed socio-economic information for each household. Each year, about 3’000 households are interviewed. To increase the sample size, our underlying data set aggregates three waves of survey data from the consecutive years 2009–2011 (BFS, 2012a, 2012b, and 2013a) using aggregation weights published by BFS (2014). We then aggregate data on consumption and income of the approximately 9’000 individual households into 14 representative household groups which are included as separate economic agents in the numerical equilibrium model (see also Table 1). For working-age households, we distinguish ten household groups based on income deciles. Retired households are split into four groups representing income quartiles. From the HABE data, we use in our model for each household group the level of expenditures by good and income by source.

INTEGRATING MICRO-HOUSEHOLD SURVEY DATA AND IO DATA.—Integrating the micro-household survey data in the macroeconomic model requires an exact match between national aggregates of demands and incomes by single households and aggregate information on household consumption and revenue according to the national accounts. National consumption in terms of COICOP (Classification of



Individual Consumption According to Purpose) categories according to the IO data was then imposed on the household data by scaling household consumption by the appropriate factor for each consumption category. Similarly, household data on wage income was scaled to meet the national aggregate. For income through capital rents, it had to be taken into account that not the whole operating surplus of industries can be associated with income for households, as some of it will be reinvested directly. Our benchmark assumes that about half of the operating surplus generates actual income to households, while the remainder is directly reinvested. Saving behavior is also represented in the household survey and was scaled to match aggregate household saving from the IO-table.<sup>4</sup>

### *B. Overview of general equilibrium model*

The key features of our multi-sector, multi-household comparative-static numerical general equilibrium model of the Swiss economy are briefly outlined below. Appendix A contains an algebraic description of the model’s equilibrium conditions.

**PRODUCTION TECHNOLOGIES AND FIRM BEHAVIOR.**—In each industry, gross output is produced using the primary inputs labor and capital and domestically produced or imported intermediate inputs. We employ constant-elasticity-of-substitution (CES) functions to characterize the production systems. All industries except electricity generation are characterized by constant returns to scale. The nesting structure of production sectors is depicted in Figure B1, Panel (a), in Appendix B.

Power generation is modeled using a simple bottom-up approach where output from each technology is produced by combining technology-specific capital with inputs of labor, fuel, and materials. Electricity generation from different technologies is treated as a homogeneous good and power supply by the technologies is determined by calibrated price elasticities of supply. The IO data provides information to calibrate production functions for electricity generating technologies that have been active in 2008. These include all electricity technologies listed in Table 1 except for “Geothermal” and “Combined heat and power” which initially do not operate but can become active if economically competitive under future policy.

Given input prices and taxes, firms minimize production costs subject to the technology constraints. Firms operate in perfectly competitive markets and maximize their profits by selling their products at a price equal to marginal costs. Fossil fuel resources and power technology capital are treated as sector-specific and in fixed supply, whereas capital outside the power sector and labor are treated as perfectly mobile across sectors within Switzerland. Our model assumes that

<sup>4</sup>The remaining difference between income and expenditure of households was attributed to direct transfers to or from the government. In our model, we index government transfers to the consumer price index thereby effectively assuming that households’ transfer income (in real terms) is unaffected by carbon taxation.

Swiss and foreign investors view investments inside or outside Switzerland as perfect substitutes. Rents are determined in the world economy and exogenous for Switzerland. They change only in line with the real exchange rate.

PREFERENCES AND HOUSEHOLD BEHAVIOR.—Given prices for goods and services and factors of production, households maximize their utility by allocating income received from government transfers, wages and rents on capital to consumption. Preferences for each representative household group are described by a nested CES utility function of consumption goods. The nesting structure for utility of consumption is depicted in Figure B1, Panel (b), in Appendix B. Households differ in terms of their expenditure and income patterns. Labor supply and savings are assumed to be fixed.

INTERNATIONAL TRADE, GOVERNMENT, AND INVESTMENT.—With the exception of crude oil, which is a homogeneous good, domestic and imported versions of goods are differentiated following the [Armington](#) assumption ([Armington, 1969](#)): for each commodity, total market supply is a CES composite of a domestically produced variety and an imported one. Swiss imports and exports do not affect world market prices. Switzerland is assumed to keep its trade balance constant and the supply of exports together with demand of imports determine the real exchange rate at which Swiss trade interacts with the global market.

All levels of government activity are represented by a single government entity. Aggregate government consumption is represented by a Leontief composite and is financed by tax and tariff revenues. Like government consumption, the composite investment good is modeled using a fixed coefficient production function. We assume that public spending and private consumption are separable and use a non-distortionary equal yield instrument to hold the level of real government spending fixed.

### *C. Representation of transport externalities*

Fossil fuel use in the transportation sector is known to cause several traffic-related externalities such as, for example, local and global air pollution, noise pollution, congestion, and accidents ([Calthrop and Proost, 1998](#); [Parry, Walls and Harrington, 2006](#)). To gauge the implications of such effects for optimal (differentiated) carbon pricing, our model includes the cost due to transport externalities.

MODELING TRANSPORT EXTERNALITIES.—Household welfare  $\mathcal{W}_h$  comprises utility derived from real consumption  $C_h$  (expressed as baseline consumption plus equivalent variation) by households  $h = 1, \dots, H$ , and averted damages from non-CO<sub>2</sub> related transport externalities according to

$$\mathcal{W}_h = [C_h - \theta_h \eta \Delta V],$$

and social welfare is described in the model as

$$(1) \quad \mathcal{W} = \sum_h \mathcal{W}_h,$$

where  $\theta_h$  is the population share of household  $h$ ,  $\eta$  is the national externality caused by one vehicle kilometer traveled, and  $\Delta V = V - V^0$  is the difference in vehicle kilometers traveled between the policy-induced level  $V$  and the “no-policy” reference level  $V^0$ . We thus assume that welfare is separable between market consumption and transport externalities.<sup>5</sup> Also note that throughout our analysis we adopt a Benthamite (utilitarian) social welfare function that simply aggregates welfare changes across households without inequality aversion.

As most of the non-climate related externalities are proportional to vehicle kilometers traveled rather than to fuel consumed (Parry and Small, 2005), we distinguish between fuel use and vehicle kilometers traveled. This is particularly important in our context where carbon tax-induced increases in fuel prices may work to increase the fuel efficiency of vehicles rather than only reduce vehicle kilometers traveled. As our model does not directly account for vehicle kilometers traveled, we need to relate changes in transport-related fuel use derived from the model to  $\Delta V$ .

Let  $Y_i$  and  $C_h$  denote the level of industrial output by sector  $i \in \mathcal{I}$  and consumption by household  $h \in \mathcal{H}$ , respectively.<sup>6</sup>  $x_n$ ,  $n \in I \cup H$ , are the respective unit demands for transportation fuels. Total fuel demand from the general equilibrium model is then given by:

$$\Psi = \sum_{i \in \mathcal{I}} Y_i x_i + \sum_{h \in \mathcal{H}} C_h x_h,$$

where we denote the corresponding “no-policy” level at reference demands  $Y_i^0$ ,  $C_i^0$ , and  $x_n^0$  by  $\Psi^0$ .

It is useful to separately identify changes in fuel use due to (i) changes in sectoral output and consumption (*scale effects*) and (ii) changes in market prices (*substitution effects*). The reason is that changes in fuel use due to scale effects translate directly into changes in  $V$ , while changes in fuel use due to substitution effects in response to higher fuel prices imply a less than proportional change in  $V$  to the extent that more fuel-efficient vehicles are adopted. We thus decompose

<sup>5</sup>This is obviously a simplifying assumption. For example, people who have been in traffic accidents are likely to change their consumption of health services and people who experience changes in traffic noise in their neighborhood are likely to change their investment behavior in sound insulation. As this paper is not focused on analyzing transport externalities per se, we leave for future research to investigate the implications of relaxing this assumption—which, if addressed in a general equilibrium context, would call for an in-depth analysis going beyond the scope of this paper (see, for example, Carbone and Smith, 2008). Moreover, welfare does not include the benefits from averted climate change due to reducing CO<sub>2</sub> emissions in Switzerland which would be negligible due to Switzerland’s tiny share in global emissions.

<sup>6</sup>In equilibrium,  $Y_i$  and  $C_h$  are determined by the zero-profit conditions (A1) and (A2), respectively, shown in Appendix A.

the change in fuel demand relative to the “no-policy” level as:

$$\begin{aligned}\Delta\Psi &\equiv \Psi - \Psi^0 \\ &\equiv \underbrace{\sum_{i \in \mathcal{I}} \Delta Y_i x_i^0 + \sum_{h \in \mathcal{H}} \Delta C_h x_h^0}_{=:\Delta\Psi_I} + \underbrace{\sum_{i \in \mathcal{I}} (Y_i^0 + \Delta Y_i) \Delta x_i + \sum_{h \in \mathcal{H}} (C_h^0 + \Delta C_h) \Delta x_h}_{=:\Delta\Psi_S}.\end{aligned}$$

*Change in fuel use due to scale effects* *Change in fuel use due to substitution effects*

We assume that the scale effect produces relative changes in vehicle kilometers traveled that are proportional to relative changes in fuel demand,

$$1 + \frac{\Delta V_I}{V^0} = 1 + \frac{\Delta\Psi_I}{\Psi^0},$$

and iso-elastic dependencies between fuel demand and vehicle kilometers driven for the substitution effect, i.e.

$$1 + \frac{\Delta V_S}{V^0} = \left(1 + \frac{\Delta\Psi_S}{\Psi^0}\right)^\beta,$$

where  $\beta$  measures the elasticity of vehicle kilometers traveled with respect to fuel use,<sup>7</sup> and  $\Delta V_I$  and  $\Delta V_S$  are the changes in vehicle kilometers driven that correspond to changes  $\Delta\Psi_I$  and  $\Delta\Psi_S$  in fuel demand due to scale and substitution effects, respectively. The total change in vehicle kilometers traveled (relative to the “no-policy” reference) as a function of the change in fuel use is given by

$$(2) \quad \frac{\Delta V}{V^0} = \frac{\Delta\Psi_I}{\Psi^0} + \left(1 + \frac{\Delta\Psi - \Delta\Psi_I}{\Psi^0}\right)^\beta - 1.$$

We can use (2) to calculate  $\eta\Delta V$  based on model-derived changes in industrial and household-level fuel demands:

$$\eta\Delta V = \underbrace{\frac{\eta V^0}{\Psi^0}}_{t_{\text{avg}}} \cdot \frac{\Delta V}{V^0} \cdot \Psi^0 = t_{\text{avg}} \cdot \left[ \frac{\Delta\Psi_I}{\Psi^0} + \left(1 + \frac{\Delta\Psi - \Delta\Psi_I}{\Psi^0}\right)^\beta - 1 \right] \cdot \Psi^0,$$

where  $t_{\text{avg}}$  is the average transportation externality per fuel use in the benchmark.

EMPIRICAL SPECIFICATION.—Using empirical estimates for  $t_{\text{avg}}$  and  $\beta$  then, in turn, enables us to compute social welfare  $\mathcal{W}$  in (1).  $t_{\text{avg}}$  denotes the marginal loss in welfare due to non-CO<sub>2</sub> related transport externalities on a per unit of

<sup>7</sup>Consistently with Parry and Small (2005),  $\beta$  can be interpreted as the ratio between the elasticity of  $V$  with respect to the consumer fuel price ( $\eta_{MF}$ ) and the own-price elasticity of demand for fuel ( $\eta_{FF}$ ), i.e.  $\beta = \eta_{MF}/\eta_{FF}$ . If fuel efficiency were fixed, then vehicle kilometers traveled would change in proportion to fuel use, so that  $\eta_{MF} = \eta_{FF}$ .

fuel use basis.<sup>8</sup> What is an empirical plausible value for  $t_{\text{avg}}$ ? Existing studies indicate that the non-climate related externalities caused by transportation are around CHF 0.049 per person kilometer traveled which translates to CHF 1.23 per liter of gasoline (ARE, 2014).<sup>9</sup> We take CHF 1.23 per liter of gasoline as our central estimate and consider for our sensitivity analysis a lower (upper) bound of 0.33 (2.21) CHF/l.<sup>10</sup> Empirical studies suggest that probably less than half of the long-run price responsiveness of gasoline consumption is due to changes in vehicle kilometers traveled, i.e.  $\beta < 0.5$  (Parry and Small, 2005). We follow Parry and Small (2005) in choosing the central case estimate as  $\beta = 0.4$  and also adopt their lower and upper bound estimates of 0.2 and 0.6.

## II. Design of Computational Experiments

### A. “Business-as-usual” reference scenario and forward calibration

The economic effects of carbon price differentiation depend on the baseline conditions for the future Swiss economy. In our comparative-static framework, we infer the baseline structure of the Swiss economy for 2008 based on historic data sources (as described in Section I.A). In a second step, we calibrate the 2008 economy forward to the target year 2030, employing estimates for GDP growth, energy demands, emissions, autonomous energy efficiency improvements, technological change in the power sector, and changing fuel prices on the world market.<sup>11</sup> Finally, our reference scenario assumes continuation of the existing ETS policy which regulates emissions from energy intensive sectors (see Table 1 for the sectors that are regulated under the ETS in our model); we assume that the annual cap is reduced by 1.74 percentage points each year based on the current trajectory for the ETS cap.<sup>12</sup> Table B1 in Appendix B summarizes our assumptions that underlie the forward calibration in the “business-as-usual”

<sup>8</sup>We assume that the marginal and the average welfare loss from the transport externality per transport activity are the same. This appears appropriate as fuel taxes will reduce traffic in remote as well as in congested areas, in noisy as well as in silent places, and in accident prone locations as well as on straight, fenced roads.

<sup>9</sup>A study of the Swiss Federal Office for Spatial Development (ARE, 2014) has estimated the external cost from private transportation (including traffic congestion, air pollution, climate-related costs, and others) to be CHF 6.6 billion in 2010 of which 81.2% were not related to climate. According to this study, the total external costs per person kilometer are CHF 0.060 and the non-climate part of this is CHF 0.049 per person kilometer. In 2010, new private vehicles in Switzerland on average carried 1.6 persons and used 6.4 liters of gasoline per 100 kilometers (BFS, 2013b). Thus, private transportation delivers at least 25 person kilometers per liter of gasoline. The costs of non-CO<sub>2</sub> related transport externalities can thus be estimated to be about CHF 1.225 per liter of gasoline.

<sup>10</sup> It is hard to quantify the range of uncertainty about estimates for the transport externalities. Based on findings from previous literature, Parry and Small (2005) suggest confidence intervals of size up to around  $(0.2 \cdot \mu, 2.5 \cdot \mu)$  for single components of non-climate related transport externalities, where  $\mu$  is the best guess estimate for the given component. Given that the Swiss estimate for transport externalities is rather high compared to the range of estimates cited by Parry and Small (2005), we choose the upper bound to the confidence interval of only 1.8 times the central estimate:  $(0.266 \cdot \mu, 1.8 \cdot \mu)$ .

<sup>11</sup>This type of forward calibration procedure has been used, for example, in Böhringer and Rutherford (2002).

<sup>12</sup>See “CO<sub>2</sub> Verordnung” (Anhang 8 zu Art. 45 Abs. 1) which regulates the Swiss ETS until 2020. We assume the same rate of change after 2020.

(*BaU*) reference scenario.

### B. Carbon tax policies

The design of our policy scenarios is motivated by carbon tax proposals under discussion in Switzerland ([Federal Council, 2015a](#)). Three types of carbon pricing policies are currently considered that differ with respect to (1) the fuel that is taxed and (2) the sectoral scope: a carbon tax for energy-intensive sectors included under the Swiss ETS; a carbon tax on thermal fuels (including natural gas, heating oil, coal, and other petrol products) in the non-ETS sectors; a carbon tax on motor fuels in the non-ETS sectors.

Against this background, we analyze policy scenarios where emissions in the ETS are capped and economy-wide emission targets are achieved by (potentially differentiated) CO<sub>2</sub> taxes on fuels consumed outside the ETS sectors. Table 2 provides an overview of the main characteristics of the six carbon tax scenarios which are further described below:

- *Transport*: Only motor fuels (of non-ETS industries) are taxed, while thermal fuels are not taxed. Emissions from ETS industries are subject to the ETS cap and its resulting endogenous permit price.
- *Thermal*: Only thermal fuels (of non-ETS industries) are taxed, while motor fuels are not taxed. Emissions from ETS industries are subject to the ETS cap and its resulting endogenous permit price.
- *Differentiated*: Motor and thermal fuels (of non-ETS industries) are taxed at different rates. The ratio of 7/30 (=0.24) between motor and thermal fuel taxes is given by existing policy proposals ([Federal Council, 2015a](#)). Emissions from ETS industries are subject to the ETS cap and its resulting endogenous permit price.
- *Uniform-ETS*: Emissions from motor and thermal fuels (of non-ETS industries) are uniformly taxed. Emissions from ETS industries are subject to the ETS cap and its resulting endogenous permit price which likely differs from the one on motor and thermal fuels.
- *Uniform*: All emissions, including those from the ETS industries, are uniformly taxed. There is one reduction target for the whole economy and no separate ETS cap.
- *Cost-Effective*: Carbon prices for motor and thermal fuels in non-ETS industries are cost-effectively differentiated. Emissions from ETS industries are subject to a cost-effectively set ETS cap<sup>13</sup> and its resulting permit price.

<sup>13</sup>The cost-effective ETS cap is determined endogenously to minimize the welfare cost in Switzerland for achieving the given emissions reduction target.

Table 2. Main characteristics of carbon pricing scenarios

Scenario label	Thermal fuel tax	Transport fuel tax	Tax ratio transport/thermal	Cap on ETS industries
<i>Transport</i>	No	Yes	1/0	-40%
<i>Thermal</i>	Yes	No	0/1	-40%
<i>Differentiated</i>	Yes	Yes	7/30	-40%
<i>Uniform_ETTS</i>	Yes	Yes	1/1	-40%
<i>Uniform</i>	Yes	Yes	1/1	endogenous
<i>Cost-Effective</i>	Yes	Yes	endogenous	endogenous

In the “business-as-usual” scenario, total emissions amount to 33 Mt CO<sub>2</sub> in 2030; this corresponds to a reduction of about 21.5% relative to 1990. Thus, further policy measures are necessary for reaching the targeted reduction of 40% with respect to 1990.<sup>14</sup> This study considers different reduction targets for energy-related CO<sub>2</sub> emissions in Switzerland and compares the economic impacts of reaching the given target using any one of the above carbon pricing schemes. Scenarios that include the ETS with a cap assume that the cap is fix and that the target has to be met by reducing non-ETS emissions only. This reflects the fact that Switzerland plans to couple its ETS with the EU’s ETS and will not be allowed to readjust its cap freely.

*Differentiated* and *Thermal* represent policy scenarios that have been proposed by the [Federal Council \(2015a\)](#). The scenario *Transport* is neither politically realistic nor can it be expected to be efficient, but it contrasts the *Thermal* scenario and together with it spans the range of different levels of CO<sub>2</sub> tax differentiation. The scenario *Uniform* represents the most efficient policy design in a first-best world without pre-existing distortions or other externalities. The scenario *Uniform\_ETTS* is expected to be somewhat less efficient but more realistic than the scenario *Uniform* as it assumes that the Swiss ETS continues to exist in the future. Finally, the *Cost-Effective* scenario allows us to contrast the scenarios that reflect proposed Swiss carbon policies with a case which cost-effectively differentiates carbon prices of motor and thermal fuels within the non-ETS sectors and chooses an cost-effective ETS cap to achieve a given reduction target at the lowest possible costs.

Our analysis assumes throughout that the revenues from CO<sub>2</sub> taxes are redistributed to households and industries. We follow here closely the redistribution scheme proposed by Swiss policy ([Federal Council, 2015a](#)) which assumes that the carbon revenue from the Swiss ETS and from taxing industries is returned to industries in proportion to wage payments (through reductions on the social security bill). Carbon revenues from taxing households’ fuel consumption are re-

<sup>14</sup>The target is formulated in terms of all greenhouse gas (GHG) emissions and requires a reduction of at least 50% by 2030 relative to 1990 of which at least 30% should come from domestic reductions. Reducing all GHGs domestically by 30% corresponds to 40% domestic reduction of CO<sub>2</sub> ([Federal Council, 2015a](#)).



Figure 1 about here.

Figure 1. Marginal welfare costs of abatement (lines) and CO<sub>2</sub> prices (filled markers) for alternative carbon pricing schemes in CHF/tCO<sub>2</sub>

*Note:* The filled markers represent the CO<sub>2</sub> prices for the corresponding policy cases.

cycled to households in a lump-sum fashion on a per-capita basis. In addition, we assume that government spending is held fixed in real terms.

### III. Central Case Results

This section presents results from our central case<sup>15</sup> which focuses on assessing the scope for differentiated carbon pricing in the Swiss economy in the presence of transport externalities and fiscal distortions emanating from interaction of carbon taxes with the pre-existing tax system. We compare total and marginal welfare abatement costs under cost-effectively differentiated and previously proposed carbon pricing schemes.<sup>16</sup>

#### A. Marginal and total welfare abatement costs

MARGINAL WELFARE COSTS AND CO<sub>2</sub> PRICES.—When introducing CO<sub>2</sub> taxes in a first-best economy without pre-existing taxes and externalities, it is a well-established result that CO<sub>2</sub> prices correspond to marginal welfare costs (MWC) of abatement and that uniform taxation of all CO<sub>2</sub> emissions leads to an equalization of marginal abatement costs and thus minimizes costs (see, for example, [Metcalf, 2009](#)). In the presence of distortionary taxes, CO<sub>2</sub> prices understate MWC of abatement ([Bovenberg and Goulder, 1996](#)). In contrast, transport externalities motivate taxing motor fuels and thus potentially work in the opposite direction calling for higher carbon taxes in the transport sector than what would be optimal with just considering tax interaction effects in a situation where pre-existing taxes cannot be motivated by an externality. To develop an understanding of the quantitative importance of tax interaction effects and transport externalities in the Swiss economy, we begin by characterizing the marginal abatement costs and CO<sub>2</sub> prices associated with each carbon pricing scheme (see Figure 1). Several important insights emerge.

First, comparing MWC, it is evident that reducing carbon in the transportation sector is significantly more expensive as compared to taxing thermal fuels (even when the averted damages from transportation are taken into account). The reason for this is that transportation demand is highly price-inelastic relative to the demand for thermal fuels and that pre-existing taxes already made consumers use

<sup>15</sup>We here employ the central case estimates for the size of the transport externalities from Section I.C. Section IV then explores how our results are affected by using lower and upper bound estimates of parameters related to transport externalities.

<sup>16</sup>Focusing on the case of Switzerland as a small open economy, we exclude by construction any arguments for tax differentiation stemming from market power on international markets.



Figure 2 about here.

Figure 2. Absolute and relative welfare costs of decarbonization (relative to *BaU*) for alternative carbon tax policies

the cheapest options for reducing fuel use.<sup>17</sup> Comparing MWC and corresponding CO<sub>2</sub> prices for the *Transport* scenario suggests a sizeable tax interaction effect that arises when imposing a CO<sub>2</sub> tax on motor fuels. For a 30% emissions reduction, the MWC costs are about 1.5 times larger than the CO<sub>2</sub> tax: CHF 609 per metric ton of CO<sub>2</sub> (CHF/tCO<sub>2</sub>) versus CHF 440/tCO<sub>2</sub>. In contrast, when the same emissions reduction is achieved by taxing only thermal fuels, tax interaction effects are small. In the *Thermal* scenario MWC are CHF 262/tCO<sub>2</sub> and the tax rate is CHF 252/tCO<sub>2</sub> for a 30% emissions reduction. As the *Uniform* scenario involves taxing both thermal and motor fuels, it represents an intermediate case with the difference between MWC and the tax rate being smaller than in the *Transport* but larger than in the *Thermal* scenario. The reason for the particularly large tax interaction effect associated with motor fuels is the high mineral oil tax in Switzerland.<sup>18</sup>

Second, for sufficiently low emissions reductions, differentiating CO<sub>2</sub> prices between motor and thermal fuels yields significantly lower MWC. For example, for reductions as low as 25%–30%, the MWC for *Uniform* are about 2.2–1.1 (2.1–1.3) times larger than under *Thermal (Differentiated)*. The MWC ranking, however, reverses for high abatement targets in excess of 35%: with an increasing stringency it becomes cost-effective to eventually also tax motor fuels more and more despite the adverse tax interacting with the mineral oil tax. As a result, uniform carbon pricing has lower MWC for high emissions reduction targets.

Third, as the ETS cap is exogenously set independent of the overall emissions reduction target, the *Uniform-ETS* scenario is likely to lead to MWC that differ from those obtained under uniform emissions pricing (even if tax interaction effects are absent). For low reduction targets, the welfare costs of reducing an additional ton of CO<sub>2</sub> are lower than under the *Uniform* scenario as it is possible to exploit relatively cheap abatement opportunities that are still left in the non-ETS sectors. With more stringent emissions targets, more abatement has to come from the non-ETS sectors at increasing marginal abatement costs, thus eventually leading to higher MWC for the *Uniform-ETS* scenario. In fact, the point where MWC curves for the *Uniform* and *Uniform-ETS* scenarios intersect shows the level of the economy-wide emissions reduction target for which the exogenously set ETS target (i.e., a 40% reduction from no-policy levels) is cost-effective.

TOTAL WELFARE COSTS.—While a MWC perspective is useful to identify for

<sup>17</sup>While the magnitude of MWC difference between the transportation and non-transportation sectors depends of course on the specific technology assumptions for modelling the transportation sector, the finding that marginal abatement costs in the transportation sector tend to be higher in the transportation sector is in line with previous studies (see, for example, Paltsev et al., 2005a; Abrell, 2010; Karplus et al., 2013).

<sup>18</sup>As of 2015, the mineral oil tax on motor fuels is CHF 0.7422 per liter while the tax on thermal fuels is only CHF 0.003 per liter.

Table 3. Welfare cost relative to economy-wide uniform carbon pricing<sup>a</sup>

Emissions level <sup>b</sup>	<i>Transport</i>		<i>Thermal</i>		<i>Differentiated</i>		<i>Uniform-ETS</i>		<i>Cost-Effective</i>	
	$\Delta$	% $\Delta$	$\Delta$	% $\Delta$	$\Delta$	% $\Delta$	$\Delta$	% $\Delta$	$\Delta$	% $\Delta$
70	1.01	256	0.16	41	0.15	38	0.22	57	-0.07	-18
65	2.09	191	0.28	25	0.06	5	0.09	8	-0.06	-5
60	-	-	-	-	0.11	5	0.01	1	-0.04	-2
55	-	-	-	-	0.36	11	0.02	1	-0.03	-1
50	-	-	-	-	0.88	18	0.17	4	-0.02	0

Notes: <sup>a</sup> $\Delta$  measures the welfare cost difference in terms of the annual consumption loss in billion 2008 CHF relative to the *Uniform* policy case. % $\Delta$  measures the percentage difference in welfare cost relative to the *Uniform* policy case. <sup>b</sup>Energy-related CO<sub>2</sub> emissions in % relative to 1990 level.

which fuel there exist quantitatively important deviations between the tax rate and MWC, total welfare costs are what matters for deciding which policy option to adopt. Figure 2 reports total welfare costs for the different carbon pricing schemes. A first important insight is that a substantial decarbonization of the Swiss economy is possible at modest costs; for example, the annual costs of reducing CO<sub>2</sub> emissions by 40% by 2030 (relative reduction to 1990 level) are about 0.5% of annual consumption or about 2008 CHF 2.0 billion per year. Total welfare costs increase more than proportionally in the stringency of the carbon policy, which reflects that it becomes increasingly difficult to substitute fossil energy with non-carbon inputs in production and consumption activities. For example, increasing the emissions reduction goal by 10 percentage points from 40% to 50% increases the annual welfare costs by a factor of 2.4.

Second, Figure 2 shows that the design of carbon pricing policies can affect costs. The largest difference arises when emissions reductions are achieved through taxing motor fuels only. Given the high marginal abatement costs in the transportation sector as well as the large adverse tax interaction effect with the mineral oil tax on motor fuels, it is not surprising to see that mitigating emissions by only taxing motor fuels are highly inefficient (e.g., the total welfare costs under *Transport* are about three times larger than under any of the other scenarios for a 35% reduction).<sup>19</sup>

Table 3 compares the welfare costs for the carbon pricing schemes relative to the *Uniform* scenario which would minimize welfare costs in a first-best setting without pre-existing tax distortions and externalities. The *Cost-Effective* scenario indicates the maximum efficiency gains that can be obtained through differentiating carbon taxes between motor and thermal fuels. Relative to uniform carbon pricing, cost-effectively differentiating carbon taxes on motor and thermal fuels can yield efficiency gains of up to 18%; for high reduction targets, the gains from tax differentiation diminish as more abatement is achieved through lowering the use of motor fuels. The *Differentiated* scenario, which closely represents the car-

<sup>19</sup>Moreover, the numerical model failed to produce a solution for reaching reduction targets of 40% and higher in scenarios *Transport* or *Thermal*. While this does not rule out that a solution exists, it illustrates the difficulty of reaching the targets by taxing one fuel type only.

Figure 3 about here.

Figure 3. CO<sub>2</sub> tax differentiation between motor and thermal fuels for cost-effective and non-cost-effective carbon pricing schemes and alternative emissions reduction targets.

Note: The red crosses indicate the cost-effective tax differentiation (*Cost-Effective* scenario) for different emissions reduction targets. The contour lines portray the welfare losses (relative to *BaU*) of reaching a 40% emissions reduction with different ETS caps and differentiation levels of CO<sub>2</sub> taxes. The remaining markers locate non-cost-effective carbon pricing scenarios on the welfare loss surface.

bon tax structure proposed by [Federal Council \(2015a\)](#), brings about a small efficiency loss of about 5% relative to uniform emissions pricing for reductions around 40%. For higher reduction targets, the proposed carbon tax differentiation would imply efficiency losses of up to 18%.

### B. Cost-effectively differentiated CO<sub>2</sub> taxes

In order to identify the cost-effective level of carbon tax differentiation (the *Cost-Effective* scenario), the contour lines in Figure 3 show welfare effects of different ETS caps (vertical axis) and tax rate ratios between taxes on motor and thermal fuels (horizontal axis) if the implemented policy has to reduce Swiss CO<sub>2</sub> emissions by 40%. Several insights emerge.

First, on the grid of analyzed policies, the smallest welfare loss is achieved by an ETS cap that is between 30–45% below no-policy emissions and a carbon tax on motor fuels that is 55–70% of the carbon tax on thermal fuels. The cost-effective ratio of carbon taxes on motor and thermal fuels is thus significantly below one. It varies, however, substantially with the reduction target. For low reduction targets of 30%, it is cost-effective to tax carbon embodied in motor fuels at about one third of the rate applied to thermal fuels. This is due to the tax interaction effect stemming from the large mineral oil tax on motor fuels. With higher reduction targets, the cost-effective tax ratio increases but it remains below unity even for ambitious reductions goals as high as 50%.

Second, while the carbon tax ratio under cost-effective scenarios (red crosses) clearly deviates from uniform emissions pricing (*Uniform* and *Uniform\_ETTS*), the welfare losses under uniform emissions pricing scenarios are not significantly higher than under the cost-effective tax scheme. The reason is that differentiating carbon taxes has two effects on social welfare: increasing the carbon tax on motor fuels increases the efficiency loss due to tax interaction but at the same time lowers the cost of transport externalities. Given our model parametrization in the central case, we thus find that moving from the cost-effective carbon tax differentiation to uniform carbon pricing yields only slight increases in social cost. Section IV provides sensitivity analysis on the parametrization of the transport externality.

Third, the currently proposed ETS cap approximately corresponds to a 40% reduction compared to our assumption about no-policy emissions and is thus well-suited for reaching a cost-effective reduction of economy-wide emissions. This also explains why, for a 40% reduction target, the *Uniform* and *Uniform\_ETTS*

scenarios are almost as efficient as the *Cost-Effective* scenario: they are relatively close to the cost-effective carbon pricing structure both in terms of differentiating CO<sub>2</sub> prices across the margins “ETS vs. non-ETS” and “thermal vs. motor fuels”.

Fourth, focusing on the welfare cost dimension (contour plots), Figure 3 provides another insight: small mistakes in policy design (e.g., choosing *Uniform* rather than *Cost-Effective*) are significantly less severe in terms of efficiency losses as compared to fundamentally flawed policy designs (e.g., choosing *Thermal* or *Transport* instead of *Cost-Effective*).

The results indicate that, when interacting with the CO<sub>2</sub> tax, the existing mineral oil tax is too high for internalizing this externality, even though, at a CHF per liter basis, the mineral oil tax (CHF 0.74 per liter) seems small compared to the externality (CHF 1.23 per liter). The fact that the cost-effective tax to address the externality in presence of a CO<sub>2</sub> tax is much smaller than the externality caused per liter of fuel use is due to two effects. On the one hand, a tax can reduce fuel use without reducing vehicle kilometers traveled. The excessively fuel-efficient car fleet necessary to achieve this causes extra cost without reducing traffic, which makes choosing an externality correcting tax below the externality-per-liter price tag welfare improving. On the other hand, tax interaction effects persist even if the activity that causes the externality could to be taxed directly.<sup>20</sup> Bovenberg and Goulder (1996) show that for the welfare maximizing correction of an environmental externality in presence of existing distortionary (labor) taxes, the tax on the polluting activity should be below the level of the Pigouvian tax. Their findings directly apply to our setting if one interprets the differentiation of the CO<sub>2</sub> tax as an adjustment of the pre-existing mineral oil tax for optimally correcting the transport externality in presence of an existing distortionary CO<sub>2</sub> tax. Both effects together mean that the difference between total taxes on motor fuels and tax on thermal fuels that corresponds to the external damages of using fuels for transportation activities creates higher costs at the margin than the externalities that it avoids. The remaining cost-effective differentiation of CO<sub>2</sub> tax by fuels indicated in Figure 3 is compensating for this.

<sup>20</sup>To prove this point, we run the model  $\beta = 1$ , thus assuming that any change in motor fuel demand is directly proportional to changes in vehicle distance traveled. For a 30% overall reduction target, the cost-effective CO<sub>2</sub> taxes would then be CHF 279.6/tCO<sub>2</sub> on motor fuel, and CHF 195.7/tCO<sub>2</sub> for thermal fuels. The difference of CHF 83.9/tCO<sub>2</sub> corresponds to CHF 0.22 per liter of motor fuel and in combination with the mineral oil tax, motor fuels are taxed CHF 0.96 more per liter than they would be if they were used as thermal fuels. This is lower than the CHF 1.23 per liter that would be the efficient extra tax on motor fuels in absence of tax interaction effects.

As the stringency of climate policy and thus the CO<sub>2</sub> taxes increase, the tax interaction effect becomes stronger: For a 50% overall CO<sub>2</sub> reduction target, cost effective CO<sub>2</sub> taxes on motor and thermal fuels are the same (at CHF 766.5/tCO<sub>2</sub>). Thus, motor fuels are only taxed CHF 0.74 more per liter than they would be if they were used as thermal fuels.

Figure 4 about here.

Figure 4. Welfare impacts by household group for carbon tax on thermal or motor fuels (35% emissions reductions)

*C. Carbon tax differentiation and household-level distributional effects: is there an efficiency-equity trade-off?*

Besides efficiency considerations, an important criterion for assessing alternative carbon pricing designs is distributional equity. In fact, the public acceptance for carbon taxes crucially depends on their distributional consequences. One major concern is typically that the incidence of energy taxes may be sharply regressive with disproportionately large burdens falling on low-income households. This typically holds true if cost of electricity and heating increase but less so if costs of transportation do. Thus, while taxing motor fuels less than thermal fuels may be desirable from an efficiency point of view, different pricing schemes may lead to divergent outcomes in terms of how the economic burden (or gains) are distributed across household groups. Unintended distributional consequences would then have to be traded-off against possible efficiency gains.

HOUSEHOLD EXPENDITURE AND INCOME PATTERNS.—Figure ??, Panel (a), in Appendix B reports the energy-related annual expenditure shares for the income deciles of working-age households and income quartiles of retired households in Switzerland. Spending patterns of Swiss households are in line with findings from other countries: low-income households spend a relatively high share of energy-related expenditures on heating and electricity whereas high-income households spend a relatively larger share on transport fuels. Expenditure shares for natural gas and electricity decline with income while expenditure shares for heating oil do not vary much with income. The largest expenditure shares for energy-related spending are on motor fuels, and the share of transport-related expenditures increases with income. Retired households have significantly lower expenditure shares for transport than do working age households. On the expenditure side, taxing thermal fuels contributes regressively to the overall redistributive effects while motor fuels are likely to have progressive effects and affect retired households less strongly.

The overall incidence of a carbon tax, however, also depends on the sources side of income impacts. Figure ??, Panel (b), in Appendix B shows that there is substantial heterogeneity among household income groups with respect to their sources of income. In particular, the top income deciles for working-age households exhibit much larger capital and much lower labor income shares; this pattern is even more pronounced across income quartiles of retired households. In addition, the share of household income from government transfers decreases with income. The overall consequence of this distribution of income factors is that when carbon taxes reduce the productivity in the economy and thus the value of labor and capital, this tends to have progressive impacts on the sources side.

CO<sub>2</sub> TAX ON MOTOR OR THERMAL FUELS.—Figure 4 shows the welfare impacts for

## Figure 5 about here.

Figure 5. Welfare effects by household group due to differentiated carbon taxes relative to *Uniform* economy-wide carbon pricing (for 40% emissions reductions)

each household income group for carbon pricing schemes that put a carbon tax on either motor fuels or thermal fuels.<sup>21</sup> Focusing on these two extreme cases is useful as the other scenarios are combination of taxing both types of fuels. To focus on how distributional equity is affected, welfare impacts are normalized (relative to the middle income groups “EH7” and “RH3” for both sets of households, respectively). We also report cases in which the carbon revenue is not returned back to households or the industry.<sup>22</sup> The cases without revenue recycling are useful to illustrate the incidence of carbon pricing itself without confounding the analysis with impacts that are driven by assumptions on how the revenue is returned.<sup>23</sup>

Without revenue recycling, we find that a carbon tax on motor fuels is slightly progressive for working households, but less so for retired households. In contrast, a thermal fuel tax is slightly regressive for working households and markedly regressive for retired households. The small regressivity for working households is due to the sources side of income impacts which are progressive: on average, lowered wages and returns to capital are absorbed more by high-income households which derive a relatively large share of income from these factors. Redistributing the carbon tax revenue on a per capita basis to households, finally, makes the overall tax incidence sharply progressive for both sets of households.

Assuming that more equitable outcomes are politically more preferable than outcomes with either more regressive or progressive impacts, we thus do not find evidence for an efficiency–equity trade-off as far as the choice between a carbon tax on thermal or motor fuels is concerned: taxing thermal fuels is more efficient than taxing motor fuels and leads to a more equitable distributional of policy impacts. Hence, a high carbon tax on motor fuels seems to be politically undesirable from both an efficiency and equity point of view.

MIXED CARBON PRICING SCHEMES.—Neither taxing only thermal fuels nor taxing only motor fuels will achieve the ambitious CO<sub>2</sub> emissions reduction targets envisaged under Swiss climate policy at reasonable cost. Carbon pricing schemes are thus likely to involve carbon taxes on both types of fuels.

We now focus on how differentiated carbon taxes affect the incidence relative to *uniform* economy-wide carbon pricing (the incidence of *Uniform* is given in Figure 4). Figure 5 reports the welfare gain for each household income group due to differentiating carbon taxes under *Cost-Effective*, *Differentiated*, and *Uniform-ETS* relative to the *Uniform* carbon pricing. The following key insights emerge. First,

<sup>21</sup>Note that following the definition of social welfare in (1), we assume that the impacts of transport externalities are distributed on a per-capita basis.

<sup>22</sup>In this case, we assume that government spending is increased by an equal amount.

<sup>23</sup>Even when revenues are recycled back to households in a lump-sum fashion, i.e. without distorting relative prices, lump-sum transfers have direct redistributive effects. Intuitively, giving the same amount of money under a per-capita recycling scheme to a poor and a rich household creates a relatively larger gain in utility for the poor household.

differentiated carbon pricing yields more regressive outcomes since increasing the carbon tax on thermal fuels while lowering the carbon tax on motor fuels places a larger burden on low-income households who spend a relatively large (small) fraction of their income on thermal (motor) fuels.

Second, the magnitude of this additional burden that is placed on low-income households is, however, small under (near) cost-effective pricing schemes (see the *Cost-Effective* and *Uniform-ETS* case). It increases in size as the degree of the tax differentiation increases, i.e., it becomes less progressive as carbon taxes on thermal fuels are raised and those on motor fuels are lowered (for example, compare the burden patterns under *Differentiated* than under *Cost-Effective* with the corresponding carbon tax ratios in Figure 3). Related to this point, we find that as the optimal carbon tax ratio decreases for lower emissions reduction targets (see Figure 3) the distribution of welfare impacts across households is skewed toward less progressive outcomes.

Fourth, as the heterogeneity in expenditure patterns for electricity and natural gas is larger among income groups of retired households, we find that the regressive effect due to carbon tax differentiation is more pronounced for retired households as compared to the group of working-age households.

Overall, while carbon tax differentiation implies somewhat less progressive outcomes, we emphasize that the size of this effect is small. In other words, while there does exist a qualitative trade-off between efficiency and equity if the objective is to distribute policy cost in favor of the poor, its quantitative dimension is rather small suggesting that equity considerations should play a second-order role only when designing cost-effective Swiss policy in the context of differentiated carbon taxation.

#### IV. Uncertainty in Transport Externalities and Implications for Differentiated CO<sub>2</sub> Pricing

The two motives for carbon tax differentiation between thermal and motor fuels (transport externalities and tax interaction with pre-existing taxes) have been shown to work in opposite directions. In light of highly uncertain estimates about the size of transport externalities as well as uncertainties about the covariation of fuel demand and vehicle kilometers traveled (Parry and Small, 2005), the question arises how the cost-effective tax differentiation varies within an empirically plausible range of assumptions that determine the relative importance of transport externalities and tax interaction effects.

The welfare impact of transport externalities in our framework depends on  $t_{\text{avg}}$ , the welfare loss per unit of fuel use if fuel use and traffic are directly proportional, and  $\beta$ , measuring relative impact of price changes on vehicle kilometers traveled and fuel demand. To check for the robustness of results, we assume “low” and “high” estimates for both  $t_{\text{avg}}$  and  $\beta$  described in Section III.<sup>24</sup>

<sup>24</sup>We have carried out additional sensitivity analysis which independently varies  $t_{\text{avg}}$  and  $\beta$  to ana-



Figure 6 about here.

Figure 6. CO<sub>2</sub> tax differentiation between motor and thermal fuels for cost-effective and non-cost-effective carbon pricing schemes for (a) weak and (b) strong transport externalities.

Note: The red crosses indicate the cost-effective tax differentiation (*Cost-Effective* scenario) for different emissions reduction targets. The contour lines portray the welfare losses (relative to *BaU*) of reaching a 40% emissions reduction with different ETS caps and differentiation levels of CO<sub>2</sub> taxes. The remaining markers locate non-cost-effective carbon pricing scenarios on the welfare loss surface..

Our results for the robustness checks are summarized in Figure 6 which, similar to Figure 3, reports on the horizontal axis the ratio between carbon taxes on thermal and motor fuels and on the vertical axis the cap for the ETS. The red crosses indicate the cost-effective tax differentiation (*Cost-Effective* scenario) for different emissions reduction targets in the presence of “Low” [Panel (a)] and “High” [Panel (b)] non-climate externalities of transportation. The blue dots show the non-cost-effective carbon pricing schemes for a 40% emissions reduction, and contour lines portray the corresponding welfare losses (relative to the *BaU*).

Comparing the two cases presented in Figure 6 with Figure 3 shows that even though some degree of tax differentiation is cost-effective under all assumptions about transport externalities, the case for differentiation becomes much weaker if externalities are high. If the transport externality is low, we find that it is cost-effective to strongly differentiate carbon taxes on motor and thermal fuels. Panel (a) of Figure 6 shows that, while the degree of tax differentiation decreases with higher emissions reduction targets (as it does for central case estimates for the transport externality), the motor fuel–thermal fuel ratio of cost-effective tax differentiation remains low even for high targets.

While *Differentiated* performs better than both *Uniform* and *Uniform-ETS* if the externality is weak, it clearly performs worse than the *Uniform* carbon pricing policies if the externality is strong and vice versa if it is weak. Due to the shape of the welfare surface in policy parameter space, the cost-effective policy for the central estimate of the transport externality (an emissions reduction of 35% among the ETS sectors and a motor fuel–thermal fuel CO<sub>2</sub> tax ratio of 0.65) has similar welfare impacts as *Differentiated* under a low transport externality but clearly outperforms *Differentiated* under the high transport externality scenario. Similarly, it has only slightly higher welfare costs than the *Uniform* and *Uniform-ETS* policies under a high transport externality scenario but outperforms them if transport externalities are low. This suggests that a loss averse social planner who is uncertain about the magnitude of the transport externality per additional fuel use is well advised to consider the cost-effective level of tax differentiation for her central estimate of transport externalities to ensure that possible mistakes in estimating the externality will cause no significant welfare losses if

lyze the relative contributions of the uncertainty of the two parameters. We find that the uncertainty associated with each parameter has a similar effect on the overall uncertainty.



the central estimate should be off.

## V. Concluding remarks

This paper analyzes the implications of differentiated carbon taxes for the economic costs of decarbonization in the context of Swiss climate policy. Employing a numerical general equilibrium model with multiple fuels, end-use sectors, heterogeneous households, and transport externalities, we assess the empirical relevance of three motives for carbon price differentiation: fiscal interactions with the existing tax code, transport externalities, and concerns about distributional equity.

Our analysis provides evidence that uniform emissions pricing may not be optimal. While tax interaction effects emanating from high pre-existing mineral oil taxes imply a differentiation in favor of motor fuels, we find—covering a range of empirically plausible estimates about the size of transport externalities in Switzerland—that the cost-effective differentiation of carbon prices for motor and thermal fuels depends strongly on the magnitude of transport externalities per unit of fuel use. For upper bound estimates on the size of transport externalities, we find that cost-effectively differentiated carbon taxes would yield outcomes close to the uniform case. The reason is that the negative effects on social welfare due tax interaction effects associated with high taxes on motor fuels are compensated by the benefits due to reducing the transport externality. Here, the main insight for policy making is that the scope for reducing the cost of decarbonization through differentiating carbon taxes is limited when transport externalities are high.

When transport externalities are low, however, the efficiency argument for differentiating carbon taxes is strong, yielding the result that tax rates on motor fuels should be, depending policy stringency, between 0.1–0.65 times as big as the carbon tax on thermal fuels. For our central estimate of the transport externality, we find that tax rates on motor fuels should be between 0.35–0.75 times as big as the carbon tax on thermal fuels. Welfare losses from choosing a uniform CO<sub>2</sub> tax rather than the cost-effective tax scheme, under these assumptions about the transport externality, are lower than if any of the two existing proposals for tax differentiation would be implemented.

Regarding the equity dimension, our analysis finds that taxing motor fuels is progressive whereas taxing thermal fuels is regressive as long as tax revenue is not redistributed to households. For decarbonization policies that involve a combination of carbon taxes on both types of fuels as well as carbon tax revenue recycling, however, we find that cost-effective policy designs do not affect much the household-level incidence relative to the case of uniform emissions pricing. While impacts are slightly less progressive for the cost-effective case (indicating a potential efficiency–equity trade-off for policy makers who want to preserve the redistributive effect of the Swiss revenue recycling scheme), we find that these effects are small. We thus conclude that, at least in the Swiss context, equity considerations should only play a second-order role when considering carbon pricing

policies that deviate from uniform carbon pricing.

While our paper may be the first to systematically analyze how carbon prices should be differentiated cost-effectively in the presence of both pre-existing taxes and transport externalities, several directions for future research appear to be fruitful. First, our focus of carbon tax differentiation between thermal and motor fuels was motivated by the Swiss policy context. An extension of our framework could analyze carbon pricing designs involving finer differentiation across, for example, fuels, sectors, and end-users of energy. Second, we do not consider revenue recycling schemes based on adjusting (distortionary) income taxes. This should have at least a second-order effect on the nature of cost-effective carbon tax differentiation derived in our analysis. Lastly, it may be interesting to explore to what extent our findings would carry over to the context of other countries and economies. The existence of high existing taxes on mineral oils used for transportation, at least for most of the European countries, and the fact that household spending patterns for energy goods are similar for industrialized, developed economies, however, suggest that our main insights would likely still apply.

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## Appendix A: MCP Equilibrium Conditions for Numerical General Equilibrium Model

We formulate the model as a system of nonlinear inequalities and characterize the economic equilibrium as a mixed complementary problem (MCP) (Mathiesen, 1985; Rutherford, 1995)<sup>25</sup> 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  $\perp$  operate to indicate complementarity between equilibrium conditions and variables. Model variables and parameters are defined in Tables A1, A2, and A3. 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 for the model are given by:

$$\begin{aligned}
 \text{(A1)} \quad & c_i^Y \geq (1 - to_i)r_i & \perp & Y_i \geq 0 & \forall i \\
 \text{(A2)} \quad & c_{hh}^C \geq PC_{hh} & \perp & C_{hh} \geq 0 & \forall hh \\
 \text{(A3)} \quad & c^G \geq PG & \perp & G \geq 0 & \\
 \text{(A4)} \quad & c^I \geq PI & \perp & I \geq 0 & \\
 \text{(A5)} \quad & c_i^A \geq PA_i & \perp & A_i \geq 0 & \forall i
 \end{aligned}$$

Where  $Y_i$ ,  $A_i$ ,  $C_{hh}$ ,  $G$ ,  $I$  denote domestic and Armington production, household and government consumption, and investment, respectively.  $to_i$  is the output tax imposed on sector  $i$  and  $PC_{hh}$ ,  $PG$ ,  $PI$  are the private and public consumption as well as investment price index.  $c$  denotes a cost function,  $r$  a revenue function. According to the nesting structures shown in Figure ??, the unit cost functions for production activities are given as:

$$c_i^Y := \left[ \theta_i^{TOP} (c_i^{TR})^{1-\sigma_i^{TOP}} + (1 - \theta_i^{TOP}) (c_i^{NTR})^{1-\sigma_i^{TOP}} \right]^{\frac{1}{1-\sigma_i^{TOP}}}$$

where

$$\begin{aligned}
 c_i^{TR} &:= \left[ \sum_{j \in benz} \theta_{ji}^{TR} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{TR}} + \left( 1 - \sum_{j \in benz} \theta_{ji}^{TR} \right) (c_i^{PUB})^{1-\sigma_i^{TR}} \right]^{\frac{1}{1-\sigma_i^{TR}}} \\
 c_i^{PUB} &:= \left[ \sum_{j \in pub} \theta_{ji}^{PUB} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{PUB}} \right]^{\frac{1}{1-\sigma_i^{PUB}}} \\
 c_i^{NTR} &:= \left[ \theta_i^{NTR} (c_i^{MAT})^{1-\sigma_i^{NTR}} + (1 - \theta_i^{NTR}) (c_i^{VAE})^{1-\sigma_i^{NTR}} \right]^{\frac{1}{1-\sigma_i^{NTR}}} \\
 c_i^{MAT} &:= \left[ \sum_{j \in mat} \theta_{ji}^{MAT} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{MAT}} \right]^{\frac{1}{1-\sigma_i^{MAT}}} \\
 c_i^{VAE} &:= \left[ \theta_i^{VAE} (c_i^{VA})^{1-\sigma_i^{VAE}} + (1 - \theta_i^{VAE}) (c_i^{EN})^{1-\sigma_i^{VAE}} \right]^{\frac{1}{1-\sigma_i^{VAE}}} \\
 c_i^{VA} &:= \left[ \theta_i^{VA} \left( \frac{(1 + tl_i)PL}{pl_i} \right)^{1-\sigma_i^{VA}} + (1 - \theta_i^{VA}) \left( \frac{(1 + tk_i)PK}{pk_i} \right)^{1-\sigma_i^{VA}} \right]^{\frac{1}{1-\sigma_i^{VA}}}
 \end{aligned}$$

<sup>25</sup>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. 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.

$$\begin{aligned}
c_i^{EN} &:= \left[ \sum_{j \in edt} \theta_{ji}^{EN} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{EN}} + \left( 1 - \sum_{j \in edt} \theta_{ji}^{EN} \right) (c_i^{FF})^{1-\sigma_i^{EN}} \right]^{\frac{1}{1-\sigma_i^{EN}}} \\
c_i^{FF} &:= \left[ \sum_{j \in coa} \theta_{ji}^{FF} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{FF}} + \left( 1 - \sum_{j \in coa} \theta_{ji}^{FF} \right) (c_i^{LQ})^{1-\sigma_i^{FF}} \right]^{\frac{1}{1-\sigma_i^{FF}}} \\
c_i^{LQ} &:= \left[ \sum_{j \in lqd} \theta_{ji}^{LQ} \left( \frac{PAS_j}{pas_j} \right)^{1-\sigma_i^{LQ}} \right]^{\frac{1}{1-\sigma_i^{LQ}}}
\end{aligned}$$

$\theta$  refers to share parameters,  $\sigma$  denotes elasticities of substitution.  $tl_i$ ,  $tk_i$ ,  $PK$  and  $PL$  are labour and capital taxes and prices, respectively. Prices denoted with an upper bar generally refer to tax-inclusive baseline prices observed in the benchmark equilibrium.

$PAS_i$  denotes the tax and carbon price inclusive Armington prices, where  $ti_i$  is the intermediate input tax and  $PA_i$  the Armington composite price of commodity  $i$ . Carbon prices differ between ETS  $ets \in i$  and non-ETS  $nets \in i$  sectors.  $p_{CO_2}^{NETS}$  and  $p_{CO_2}^{ETS}$  denote the carbon prices for ETS and non-ETS industries<sup>26</sup>, respectively, and  $\phi_i$  the carbon coefficient. The price of non-ETS industries additionally includes the mineral oil tax  $p_{mo_i}$ . Hence, Armington prices for ETS and non-ETS sectors are defined as:<sup>27</sup>

$$\begin{aligned}
PAS_i &:= (1 + ti_i) PA_i + \phi_i p_{CO_2}^{NETS} + p_{mo_i} & \forall i \in nets \\
PAS_i &:= (1 + ti_i) PA_i + \phi_i p_{CO_2}^{ETS} & \forall i \in ets
\end{aligned}$$

On the output side, producers differentiate between supply to the domestic and supply to export market using a constant elasticity of transformation function. Denoting the domestic product price by  $PD_i$  and the exchange rate by  $PFX$  the unit revenue function is defined as:

$$r_i := \left[ \theta_i^D (PD_i)^{1+\sigma_i^T} + (1 - \theta_i^D) (PFX)^{1+\sigma_i^T} \right]^{\frac{1}{1+\sigma_i^T}}$$

Trade is modelled via the Armington approach using a CES function between domestically produced and imported commodities. Denoting  $tm_i$  as import tax, the cost function of the Armington aggregation becomes:

$$c_i^A := \left[ \theta_i^D (PD_i)^{1-\sigma^A} + (1 - \theta_i^D) \left( \frac{(1 + tm_i) PFX}{pm_i} \right)^{1-\sigma^A} \right]^{\frac{1}{1-\sigma^A}}$$

According to the nesting structures shown in Figure ??, the unit cost functions for production activities are given as:

$$c_{hh}^C := \left[ \theta_{i,hh}^{CTOP} (c_{hh}^{CTR})^{1-\sigma^{CTOP}} + (1 - \theta_{i,hh}^{CTOP}) (c_{hh}^{CNTR})^{1-\sigma^{CTOP}} \right]^{\frac{1}{1-\sigma^{CTOP}}}$$

where

$$\begin{aligned}
c_{hh}^{CTR} &:= \left[ \sum_{i \in benz} \theta_{i,hh}^{CTR} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CTR}} + \left( 1 - \sum_{i \in benz} \theta_{i,hh}^{CTR} \right) (c_{hh}^{CPUB})^{1-\sigma^{CTR}} \right]^{\frac{1}{1-\sigma^{CTR}}} \\
c_{hh}^{CPUB} &:= \left[ \sum_{i \in publ} \theta_{i,hh}^{CPUB} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CPUB}} \right]^{\frac{1}{1-\sigma^{CPUB}}}
\end{aligned}$$

<sup>26</sup>While the carbon price for the non-ETS sectors is exogenously defined, the carbon price for the ETS industries results from the cap  $e_{max}^{ETS}$  of the emission trading system.

<sup>27</sup>For ease of notation we suppress the fact that taxes and carbon coefficients are differentiated by agent.

$$\begin{aligned}
c_{hh}^{CNTR} &:= \left[ \theta_{hh}^{CNTR} (c_{hh}^{CMAT})^{1-\sigma^{CNTR}} + (1 - \theta_{hh}^{CNTR}) (c_{hh}^{CEN})^{1-\sigma^{CNTR}} \right]^{\frac{1}{1-\sigma^{CNTR}}} \\
c_{hh}^{CMAT} &:= \left[ \sum_{i \in mat} \theta_{i,hh}^{CMAT} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CMAT}} \right]^{\frac{1}{1-\sigma^{CMAT}}} \\
c_{hh}^{CEN} &:= \left[ \sum_{i \in edt} \theta_{i,hh}^{CEN} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CEN}} + \left( 1 - \sum_{i \in edt} \theta_{i,hh}^{CEN} \right) (c_{hh}^{CFF})^{1-\sigma^{CEN}} \right]^{\frac{1}{1-\sigma^{CEN}}} \\
c_{hh}^{CFF} &:= \left[ \sum_{i \in coa} \theta_{i,hh}^{CFF} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CFF}} + \left( 1 - \sum_{i \in coa} \theta_{i,hh}^{CFF} \right) (c_{hh}^{CLQ})^{1-\sigma^{CFF}} \right]^{\frac{1}{1-\sigma^{CFF}}} \\
c_{hh}^{CLQ} &:= \left[ \sum_{i \in lq} \theta_{i,hh}^{CLQ} \left( \frac{PAS_i}{pas_i} \right)^{1-\sigma^{CLQ}} \right]^{\frac{1}{1-\sigma^{CLQ}}}
\end{aligned}$$

For government and investment consumption fixed shares are assumed:

$$\begin{aligned}
c^G &:= \sum_i \theta_i^{GTOP} \frac{PAS_i}{pas_i} \\
c^I &:= \sum_i \theta_i^{ITOP} \frac{PAS_i}{pas_i}
\end{aligned}$$

Denoting each households initial endowments of labor and capital as  $\bar{l}_{hh}$  and  $\bar{k}_{hh}$ , respectively,  $INCC_{hh}^C$  and  $INCC_{hh}^G$  as consumer and government income and using Shephard's lemma, market clearing equations become:

$$\begin{aligned}
(A6) \quad A_i &\geq \sum_j \frac{\partial c_j}{\partial PA_i} Y_j + \sum_{hh} \frac{\partial c_{hh}^C}{\partial PA_i} C \\
&\quad + \frac{\partial c^G}{\partial PA_i} G + \frac{\partial c^I}{\partial PA_i} I \quad \perp \quad PA_i \geq 0 \quad \forall i
\end{aligned}$$

$$(A7) \quad \frac{\partial r_i}{\partial PD_i} Y_i \geq \frac{\partial c_i^A}{\partial PD_i} A_i \quad \perp \quad PD_i \geq 0 \quad \forall i$$

$$(A8) \quad \sum_{hh} \bar{l}_{hh} \geq \sum_i \frac{\partial c_i}{\partial PL} Y_i \quad \perp \quad PL \geq 0$$

$$(A9) \quad \sum_{hh} \bar{k}_{hh} \geq \sum_i \frac{\partial c_i}{\partial PK} Y_i \quad \perp \quad PK \geq 0$$

$$(A10) \quad I \geq \sum_{hh} \bar{i}_{hh} \quad \perp \quad PI \geq 0$$

$$(A11) \quad C_{hh} \geq \frac{INCC_{hh}^C}{PC_{hh}} \quad \perp \quad PC_{hh} \geq 0 \quad \forall hh$$

$$(A12) \quad G \geq \frac{INCC^G}{PG} \quad \perp \quad PG \geq 0$$

$$(A13) \quad \sum_i \frac{\partial r_i}{\partial PFX} Y_i \geq \sum_i \frac{\partial c_i^A}{\partial PFX} A_i + \bar{bop} \quad \perp \quad PFX \geq 0$$

$$(A14) \quad e_{max}^{ETS} \geq \sum_i \phi_i^{ETS} \sum_{j \in ets} \frac{\partial c_j}{\partial PA_i} Y_j \quad \perp \quad PCO_2^{ETS} \geq 0$$

Carbon emissions of non-ETS industries are given by:

$$(A15) \quad E^{NETS} := \sum_i \phi_i^{NETS} \left[ \sum_{j \in nets} \frac{\partial c_j}{\partial PA_i} Y_j + \sum_{hh} \frac{\partial c_{hh}^C}{\partial PA_i} C_{hh} + \frac{\partial c^G}{\partial PA_i} G + \frac{\partial c^I}{\partial PA_i} I \right]$$

Private income is given as factor income net of investment expenditure and a lumpsum or direct tax payment to the local government. Public income is given as the sum of all tax revenues:

$$(A16) \quad \begin{aligned} INC_{hh}^C &:= P\bar{L}\bar{s}_{hh} + P\bar{K}\bar{k}s_{hh} - P\bar{I}\bar{i}_{hh} - P\bar{C}_{hh}\bar{htax}LSM \\ INC^G &:= \sum_i to_i \left( PD_i \frac{\partial r_i}{\partial PD_i} Y_i + PFX \frac{\partial r_i}{\partial PFX} Y_i \right) \\ &+ \sum_i ti_i PA_i \left[ \sum_j \frac{\partial c_j}{\partial PA_i} Y_j + \frac{\partial c^C}{\partial PA_i} C + \frac{\partial c^G}{\partial PA_i} G + \frac{\partial c^I}{\partial PA_i} I \right] \\ &+ \sum_i tm_i PFX \frac{\partial c_i^A}{\partial PFX} A_i \\ &+ \sum_i Y_i \left[ tlPL \frac{\partial c_i}{\partial PL} + tkPK \frac{\partial c_i}{\partial PK} \right] \\ &+ P\bar{C}\bar{htax}LSM + P\bar{F}X\bar{bop} \\ &+ p_{CO_2}^{NETS} E^{NETS} \\ &+ p_{CO_2}^{ETS} e_{max}^{ETS} \\ (A17) \quad &+ \sum_i \bar{p}\bar{m}\bar{o}\mu_i Y_i \end{aligned}$$

$\bar{htax}$  is a lumpsum tax on the representative household, i.e. a lumpsum payment from the household to the government. The multiplier  $LSM$  is used to implement revenue recycling in a lumpsum manner and determine by:

$$(A18) \quad G = 1 \quad \perp \quad LSM \text{ free}$$

If revenues are not recycled but change government purchases, the multiplier is fixed and the preceding is dropped.



Table A1. Sets, and price and quantity variables

Symbol	Description
<i>Sets</i>	
$i \in I$	Commodities
$hh \in H$	Households
$ets \subset I$	Industries within the emission trading system (ETS)
$nets \subset I$	Non-ETS Industries
$benz \subset I$	Motor fuels
$publ \subset I$	Public transport commodities
$mat \subset I$	Material input commodities
$edt \subset I$	Electricity consumption commodities
$coa \subset I$	Coal commodities
$lq \subset I$	Liquid fuel commodities
<i>Prices and quantities</i>	
$PA_i$	Armington price of commodity $i$
$PAS_i$	Tax and carbon cost inclusive Armington price of commodity $i$
$PL$	Wage rate
$PC_{hh}$	Consumer price index of household $hh$
$p_{CO_2}^{ETS}$	Carbon price in ETS
$PG$	Public consumption price index
$PI$	Investment consumption price index
$PK$	Capital rental rate
$PD_i$	Domestic product price of commodity $i$
$PFX$	Exchange rate
$G$	Public consumption
$C$	Private consumption
$A_i$	Armington commodity production $i$
$I$	Investment consumption
$Y_i$	Production of sector $i$
$INC_{hh}^C$	Private income of household $hh$
$INC^G$	Public income
$E^{NETS}$	Total carbon emissions of non-ETS industries
$LSM$	Lump sum multiplier

Table A2. Model parameters

Symbol	Description
<i>Elasticity of substitution parameters</i>	
$\sigma_i^{TOP}$	Top level (transport vs. non-transport inputs) in sector $i$
$\sigma_i^{VA}$	Value added composite in production sector $i$
$\sigma_i^{VAE}$	Value added vs. energy composite in production sector $i$
$\sigma_i^{EN}$	Energy composite in production sector $i$
$\sigma_i^{FF}$	Fossil fuel composite in production sector $i$
$\sigma_i^{LQ}$	Liquid fuel composite in production sector $i$
$\sigma_i^{TR}$	Transport composite in production sector $i$
$\sigma_i^{NTR}$	Non-transport composite in production sector $i$
$\sigma_i^{MAT}$	Material composite in production sector $i$
$\sigma_i^{PUB}$	Public transport composite in production sector $i$
$\sigma^{CTOP}$	Top level consumption (transport vs. non-transport)
$\sigma^{CEN}$	Energy composite in consumption
$\sigma^{CFF}$	Fossil fuel composite in consumption
$\sigma^{CTR}$	Transport composite in consumption
$\sigma^{CNTR}$	Non-transport composite in consumption
$\sigma^{CMAT}$	Material composite in consumption
$\sigma^{CPUB}$	Public transport composite in consumption
$\sigma^{CLQ}$	Liquid fuel composite in consumption
$\sigma_i^T$	Elasticity of transformation between domestic and export markets
$\sigma_i^A$	Domestic vs. imported commodity $i$
<i>Input and expenditure shares</i>	
$\theta_i^{TOP}$	Share of commodity $j$ in top-level production $i$
$\theta_{ji}^{TR}$	Share commodity $j$ cost in transport cost bundle
$\theta_{ji}^{PUB}$	Shares of commodity $j$ in public transport cost bundle
$\theta_{ji}^{NTR}$	Shares of material commodities in non-transport cost bundle
$\theta_{ji}^{MAT}$	Shares of commodity $j$ in material cost bundle
$\theta_{ji}^{VAE}$	Share of value-added cost in value-added/energy cost bundle
$\theta_{ji}^{VA}$	Share of labor cost in value added cost bundle
$\theta_{ji}^{EN}$	Share of commodity $j$ cost in energy bundle
$\theta_{ji}^{FF}$	Share of commodity $j$ cost in fossil fuel bundle
$\theta_{i,hh}^{CTOP}$	Expenditure share of commodity $i$ in top-level consumption of $hh$
$\theta_{i,hh}^{CTR}$	Expenditure share of commodity $i$ in transport consumption
$\theta_{i,hh}^{CPUB}$	Expenditure shares of commodity $i$ in public transport consumption
$\theta_{hh}^{CNTR}$	Expenditure share of materials in non-transport consumption
$\theta_{i,hh}^{MAT}$	Expenditure shares of commodity $i$ in material consumption
$\theta_{i,hh}^{CEN}$	Expenditure share of commodity $j$ in energy consumption
$\theta_{i,hh}^{CFF}$	Expenditure share of commodity $j$ in fossil fuel consumption
$\theta_i^D$	Share of domestically supplied products
$\theta_i^G$	Expenditure share commodity $i$ in public consumption
$\theta_i^I$	Expenditure share commodity $i$ in investment consumption
<i>Other parameters</i>	
$\bar{i}_{hh}$	Reference investment level per household $hh$
$htax_{hh}$	Direct tax from household $hh$ to government
$e_{max}^{ETS}$	Emission cap in ETS
$\phi_i$	Carbon coefficient of commodity $i$
$\overline{pas}_i$	Armington price inclusive of reference taxes and carbon cost
$\overline{pl}$	Tax-inclusive reference price for labor
$\overline{pk}$	Tax-inclusive reference price for capital
$\overline{pm}_i$	Tax-inclusive import price of commodity $i$
$pCO_2^{NETS}$	Carbon price in non-ETS industries
$pmo_i$	Mineral oil tax of commodity $i$
$tl_i$	Labor use tax in production $i$
$tk_i$	Capital use tax in production $i$
$ti_i$	Use tax for commodity $i$
$to_i$	Output tax imposed on sector $i$
$tm_i$	Import tax for commodity $i$

Table A3. Parameter values for substitution elasticities in production and consumption

Parameter	Description	Value
<i>Production</i>		
$\sigma_i^{TOP}$	Top level (transport vs. non-transport inputs) in sector $i$	0.1
$\sigma_i^{VA}$	Value added composite in production sector $i$	0.5
$\sigma_i^{VAE}$	Value added vs. energy composite in production sector $i$	0.5
$\sigma_i^{EN}$	Energy composite in production sector $i$	0.5
$\sigma_i^{FF}$	Fossil fuel composite in production sector $i$	0.2
$\sigma_i^{LQ}$	Liquid fuel composite in production sector $i$	0.8
$\sigma_i^{TR}$	Transport composite in production sector $i$	0.9
$\sigma_i^{NTR}$	Non-transport composite in production sector $i$	0.5
$\sigma_i^{MAT}$	Material composite in production sector $i$	0.3
$\sigma_i^{PUB}$	Public transport composite in production sector $i$	0.8
$\sigma_i^T$	Elasticity of transformation between domestic and export markets <sup>a</sup>	0.4-2
$\sigma_i^A$	Domestic vs. imported commodity $i$ <sup>a</sup>	0.5-4
<i>Consumption</i>		
$\sigma^{CTOP}$	Top level consumption (transport vs. non-transport)	0.1
$\sigma^{CEN}$	Energy composite in consumption	0.5
$\sigma^{CFF}$	Fossil fuel composite in consumption	0.2
$\sigma^{CTR}$	Transport composite in consumption	0.9
$\sigma^{CNTR}$	Non-transport composite in consumption	0.5
$\sigma^{CMAT}$	Material composite in consumption	0.5
$\sigma^{CPUB}$	Public transport composite in consumption	0.8
$\sigma^{CLQ}$	Liquid fuel composite in consumption	0.8

Notes: <sup>a</sup>Elasticities are sector specific. We report the range of all values.

## Appendix B: Additional tables and figures

Table B1. Assumptions underlying forward calibration to year 2030 in the “business-as-usual” scenario.

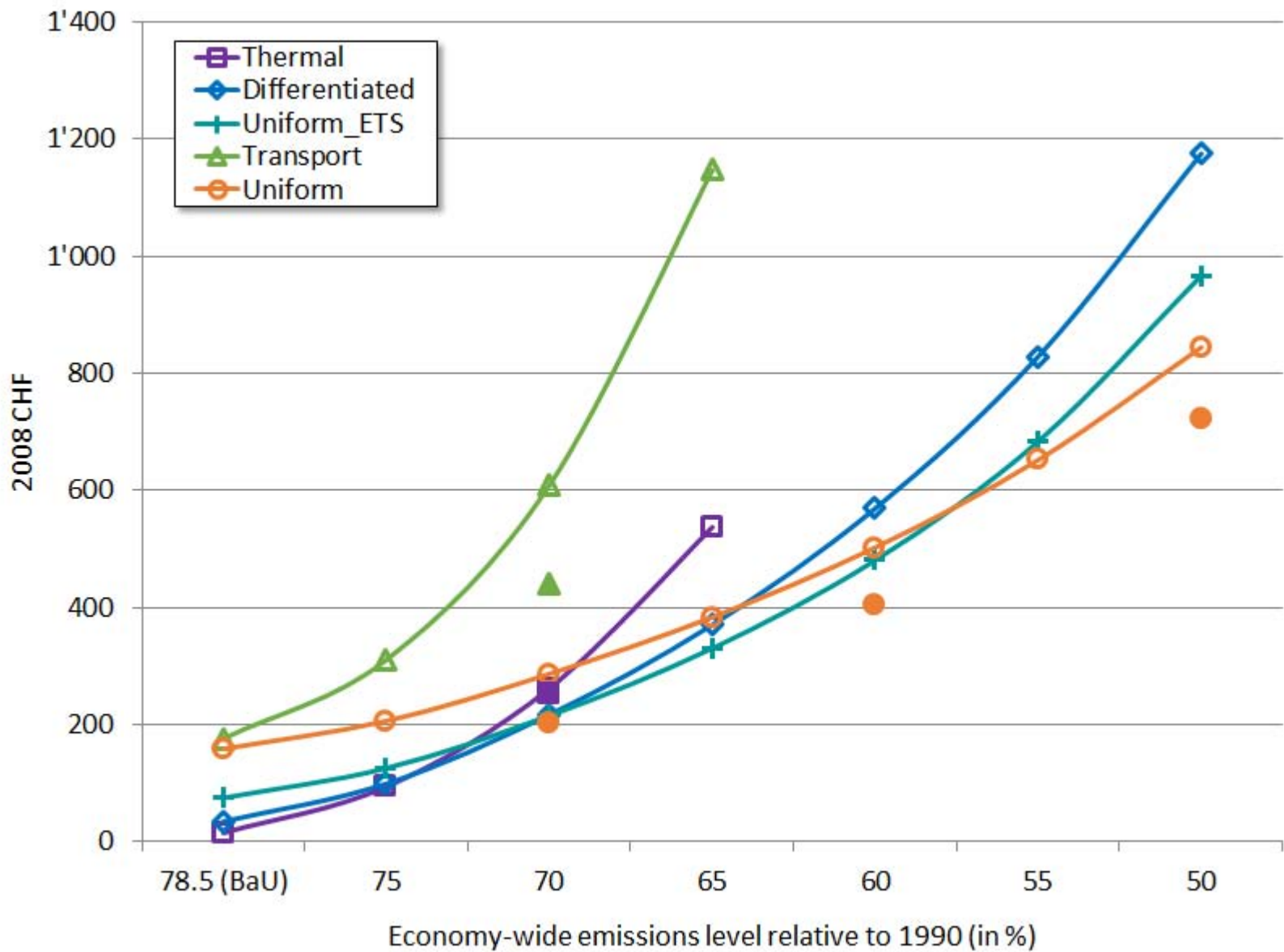
Electricity generation share in % for 2030 (2008)		GDP growth, energy demands, fuel prices, and ETS emissions (% $\Delta$ relative to 2008)	
Hydro storage	27.8 (38.0)	Electricity demand	6.7
Running hydro	16.2 (24.0)	Gas demand	76.9
Nuclear	6.6 (34.2)	Coal demand	-30.3
Combined-cycle turbines	24.4 (-)	Motor fuel demand	-24.3
Combined heat and power	10.2 (0.2)	Light fuel oil demand	-57.7
Other fossil	0.5 (3.1)	Other petrol demand	4.7
Biofuel (Wood)	9.2 (0.1)	Global gas price	28.7
Solar	2.8 (0.3)	Global oil price	8.3
Wind	1.6 (0.1)	Global coal price	8.3
Geothermal	0.5 (-)	GDP growth	23.4
		CO <sub>2</sub> emissions in ETS	-32.0

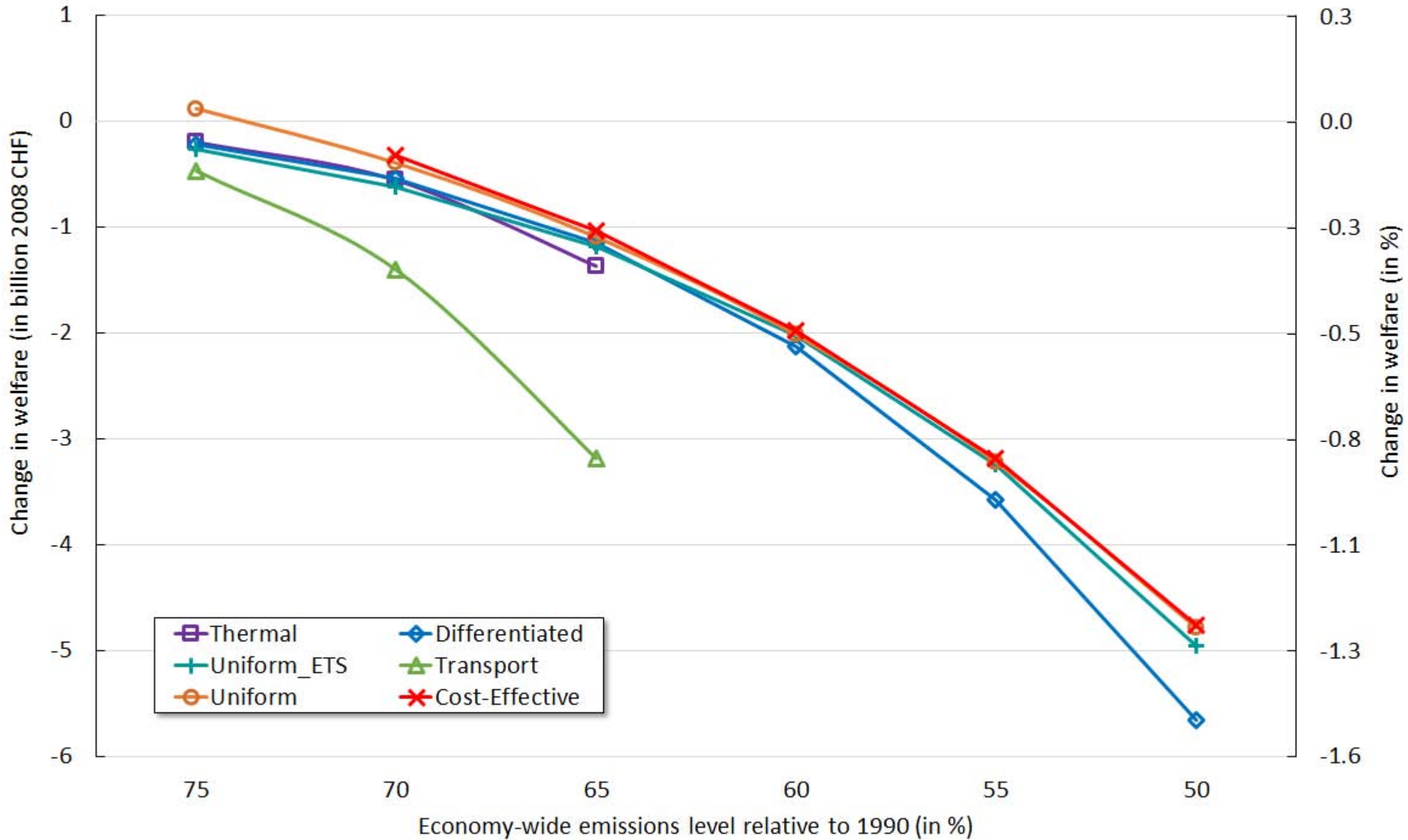
Figure B1 about here.

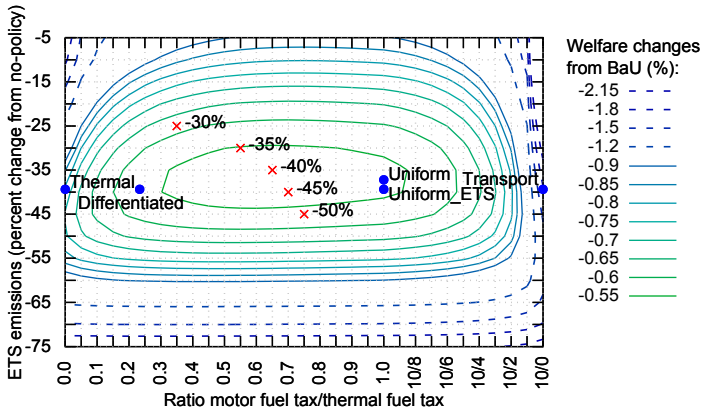
Figure B1. Nested structure for production and consumption activities

Figure B2 about here.

Figure B2. Benchmark energy-related expenditure shares and income shares by household group









Percentage point difference in welfare impact relative to EH7 and RH3 (EH7=0 and RH3=0)

