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Is a Uniform Carbon Tax a Good Idea? The Case of Switzerland[*]

By Florian Landis, Sebastian Rausch, and Mirjam Kosch[†]

This paper analyzes the implications of differentiated carbon taxes for the economic costs of decarbonization, using Swiss climate policy as an example. Employing a numerical general equilibrium model with multiple fuels, end-use sectors, and heterogeneous households, we assess the empirical relevance of three motives for carbon price differentiation: fiscal interactions with the existing tax code, transportation externalities, and concerns about distributional equity. We find that cost-effective climate policy entails substantially lower taxes on motor than on thermal fuels (by a factor of 0.1–0.6) and that uniform carbon pricing forgoes sizeable efficiency gains (between 5–41 percent). The case for carbon tax differentiation is robust but somewhat weakened if emissions reduction targets are ambitious or if non-climate transportation externalities are taken into account.

A fundamental tenet of environmental economics concerning the regulation of a uniformly dispersed pollutant such a carbon dioxide (CO_2) 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_2 emissions, international spillover effects (Markusen, 1975; Hoel, 1996), or 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 clear results about the magnitude of overall effects can be obtained. The ambiguity predicted by Lipsey and Lancaster (1956)'s general theory of the second best, suggests that the answer to

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such questions strongly depends on the specific context, i.e. the type of externalities and distortions in a specific economy and environmental policy context.

Our analysis uses the example of climate policy in Switzerland to provide an empirical context in which the effects of differentiated carbon pricing can be illustrated. A common feature of current and past Swiss carbon tax policy proposals (Federal Council, 2015*a*,*b*; Imhof, 2012) is to differentiate carbon prices by fuel type such that motor fuels are taxed at a much smaller rate as compared to fuels used for non-transportation purposes. The tax interaction with preexisting taxes on motor fuels has been identified as a reason for carbon price differentiation before (in the Swiss context by Imhof (2012),[1] in the European context by Paltsev et al. (2005*b*); Abrell (2010)). We elaborate on these previous efforts by systematically looking for the optimal level of carbon price differentiation between motor and thermal fuels. With regard to the political process, we do not want to provide arguments for new dimensions along which to differentiate carbon prices—arguments, which could be high-jacked by lobby groups (Boeters, 2014). We instead provide an analysis of existing proposals for carbon price differentiation and give advice on how to improve them from an economic perspective.

We further consider how the economic rationale for carbon price differentiation is altered by the presence of other externalities that are not related to CO_2 emissions. We also investigate to what extent carbon price differentiation may involve a trade-off between efficiency and equity, focusing on impacts among household groups with different income. Expenditure shares for heating and electricity tend to be higher for poorer as compared to richer households, in turn leading to a regressive incidence of rising prices on the uses side (Metcalf, 1999; Rausch, Metcalf and Reilly, 2011; Fullerton, Heutel and Metcalf, 2012). For taxes on motor fuels, on the other hand, we would not predict this regressivity in many OECD countries (Sterner, 2012). Hence, while differentiating carbon prices between fuels may enhance efficiency, it 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. Household heterogeneity is captured by differentiating 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.

Our analysis provides clear support in favour of carbon tax differentiation. Cost-effective climate policy, in the Swiss context, entails substantially lower taxes on

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[1] Other recent studies 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); Sceia et al. (2012) analyze transportation-specific emission reduction targets and find them to be an inefficient deviation from uniform carbon pricing.

motor fuels than on thermal fuels (by a factor of 0.1–0.6). We find that uniform carbon pricing forgoes sizeable efficiency gains on the order of 5–41% relative to optimally differentiated carbon taxes, depending on the stringency of climate policy. The main driver behind this result is a tax interaction effect that creates additional efficiency losses due to a "double" taxation of transport fuels through mineral oil and carbon taxes.

The case for carbon tax differentiation remains robust but is somewhat weakened if emissions reduction targets are large or if non-climate transportation externalities are taken into account. If we assume that the mineral oil tax on motor fuels is pricing an externality, we find that CO_2 taxes should be differentiated much less and that a uniform carbon tax is closer to the optimum than a differentiated tax structure as is proposed by Swiss climate policy. We do not find evidence for an efficiency–equity trade-off as far as the differentiation between carbon taxes on motor and thermal fuels is concerned. A carbon tax on transport fuels is cost-ineffective compared to a carbon tax on thermal fuels and leads to a more dispersed distributional outcome. Carbon pricing policies that are only based on taxing transport fuels are hence also undesirable from the viewpoint of distributional equity. For the analyzed carbon pricing schemes, distributional impacts by household income group are dominated by the progressive effects from carbon revenue recycling.

A small but growing literature has been using 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 optimal 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).[2] Our paper adds to the literature by identifying a politically relevant case where

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[2] 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.

carbon price differentiation is efficient and by determining the optimal level of carbon price differentiation.

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–V present simulation results and discuss the relevance of the various motives for carbon tax differentiation. Section VI concludes.

I. Quantitative Framework

This section provides an overview of the numerical general equilibrium model 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.

A. Data

This study makes use of a comprehensive data set which combines survey data describing single households and national accounts describing spending and income of industries, the government and households in aggregate. On the household side, a representative sample of the Swiss population of households is portrayed by the 2009–2011 Swiss Household Budget Survey "Haushaltsbudgeterhebung (HABE)". The aggregate value flows are given by the Social Accounting Matrix data for the Swiss economy, and they are complemented by physical energy flow data from the NAMEA (Nathani et al., 2013).

MICRO-HOUSEHOLD DATA FROM THE "HABE" SURVEY.—The HABE data is a representative survey of the permanent resident population of Swiss households which is conducted every year on an annual basis by the Swiss Federal Statistical Office (BFS). It collects information about consumer behaviour and the income of private households in Switzerland; about 3'000 households take part each year.[3] To increase sample size, our underlying data set aggregates three waves of survey data from the consecutive years 2009-2011 (BFS, 2012*a*, 2012*b*, and 2013*a*). For the aggregation over multiple years, household data we use weights published by BFS (2014). Individual households are aggregated into 14 representative household groups which are included as separate economic agents in the numerical equilibrium model (see also Table 1). For wage and salary earners, we distinguish ten household groups based on income deciles; retired households are split into four groups representing income quartiles. The individual households are mapped to aggregated household groups according to an indicator for the standard of living comprising information on total household income and expenditures. The indicator controls for household size by means of the "OECD-modified equivalence scale", an equivalence scale used by the OECD (2009) and originally proposed by

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[3] Household data is weighted according to the inclusion probability as well as taking into account certain other variables which may lead to a household not taking part in the survey.

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

Sectors ($i \in I$)	
Non-energy	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 transportion* (atp)
Energy supply & conversion	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)
Final demand	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 ($h \in H$)	Wage and salary earners 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.

Hagenaars, de Vos and Zaidi (1994).[4]

NATIONAL ECONOMIC ACCOUNTS AND ENERGY DATA.—We use the Swiss Input-Output (IO) table for the year 2008 (BFS, 2011) in the version by Nathani et al. (2013) which provides information on economic transactions among businesses, households, and government agents. Besides a detailed disaggregation of the energy and transportation industries, this version includes supplemental physical accounts for energy production and consumption which are consistently linked with economic data in value terms and to keep track of CO_2 emissions derived from physical energy quantities. In its original form, the IO table distinguishes 66 industries and commodity groups and 20 categories for final demand. 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, or are subject to the Swiss emissions trading system (ETS). Three final demand sectors represent private and government consumption, and investment demand. Based on the social accounting data, our model further includes payroll

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[4] This scale assumes the existence of economies of scale in household consumption. The mapping of households into groups is based on the reference person of the household which is defined to be the person with the highest income in that household.

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.

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. The remaining difference between income and expenditure of households was attributed to direct transfers to or from the government.

B. Model

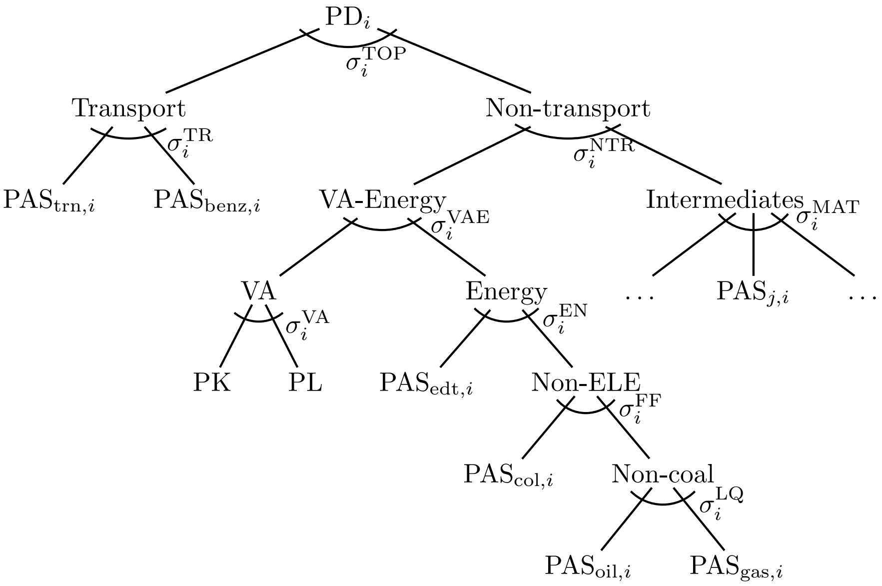
The key features of our multi-sector, multi-household comparative-static numerical general equilibrium model of the Swiss economy are briefly outlined below. Appendix A contains a complete algebraic description of the model's equilibrium conditions.

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 1a.

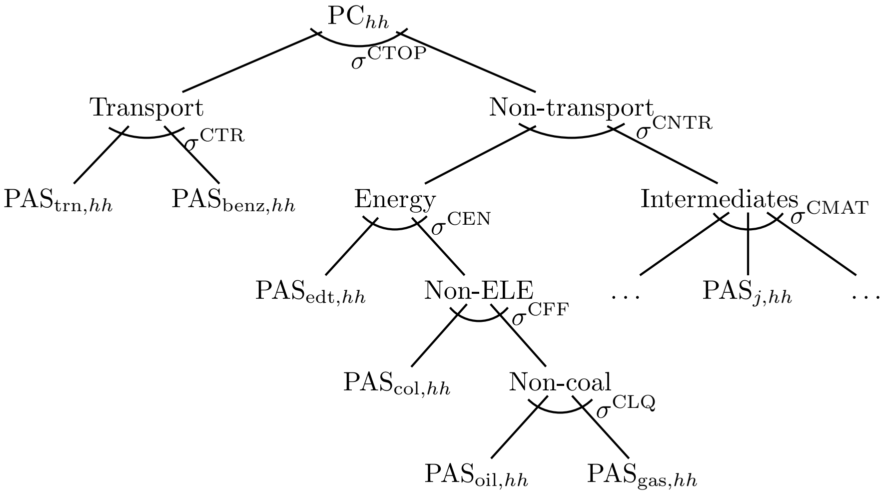
Power generation is modeled using a simple bottom-up approach where output from each technology is produced by combining technology-specific capital with inputs of labor, fuel, and materials. Electricity generation from different technologies is treated as a homogeneous good and power supply by the technologies 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: "hydro storage", "running hydro", "nuclear", "photovoltaics", "wind", "biofuel", "heat-and-power co-generation", and "other fossil fuel plants". "Geothermal" and "combined cycle turbines" technologies are included and may become active in the future (depending on baseline assumptions and their respective price elasticity of supply).

Figure 1. Nested structure for production and consumption activities

(a) Production



(b) Consumption



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 Swiss and foreign investors view investments inside or outside Switzerland as perfect substitutes. This implies that rents on broad capital are constant and determined by the real exchange rate.

PREFERENCES AND HOUSEHOLD BEHAVIOR.—Given goods and factors prices, 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 (see Figure 1b). 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.

A single government entity approximates government activities at all levels (federal, cantonal, and local). 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.

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.[5] Finally, our reference scenario assumes continuation of the existing ETS policy which regulates emissions from energy intensive sectors (see Table

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[5] This type of forward calibration procedure has been used, for example, in Böhringer and Rutherford (2002).

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.[6] Table B1 in Appendix B summarizes our assumptions that underlie the forward calibration in the "business-as-usual" (*BaU*) reference scenario.

In the "business-as-usual" scenario, total emissions amount to 33 Mt CO_2 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.[7]

B. *Alternative carbon pricing schemes*

The design of our policy scenarios is motivated by carbon tax proposals under discussion in Switzerland (Federal Council, 2015*a*). Three types of carbon pricing policies are currently considered that differ with respect to the fuel that is taxed and the sectoral scope: (1) a carbon price for energy-intensive sectors included under the Swiss ETS, and (2) a carbon tax on thermal fuels (including natural gas, heating oil, coal, and other petrol products) in the non-ETS sectors, (3) 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 overall emission targets are reached by setting endogenous but differentiated CO_2 taxes on fuels consumed outside the ETS. Our six scenarios can be described as follows (Table 2 provides a summary of their main characteristics):

- *Transport*: Only motor fuels (of non-ETS industries) are taxed, while thermal fuels are not. 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. 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, 2015*a*). 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

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[6] See "CO_2 Verordnung" (Anhang 8 zu Art. 45 Abs. 1) which regulates the Swiss ETS until 2020. We assume the same rate of change after 2020.

[7] 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_2 (Federal Council, 2015*a*).

Table 2. Main characteristics of carbon pricing scenarios

Scenario label	Thermal fuel tax	Transport fuel tax	Tax ratio transport/thermal	Cap on ETS industries
Transport	No	Yes	1/0	-40%
Thermal	Yes	No	0/1	-40%
Differentiated	Yes	Yes	7/30	-40%
Uniform_ETS	Yes	Yes	1/1	-40%
Uniform	Yes	Yes	1/1	endogenous
Optimal	Yes	Yes	endogenous	endogenous

the ETS cap and its resulting endogenous permit price which likely differs from the one on motor and thermal fuels.

- *Uniform*: All carbon emissions, including those from the ETS industries, are uniformly taxed. There is one reduction target for the whole economy and no separate ETS cap.
- *Optimal*: Carbon prices for motor and thermal fuels in non-ETS industries are optimally differentiated. Emissions from ETS industries are subject to an optimally set ETS cap and its resulting permit price.

When comparing the alternative carbon pricing schemes listed above, we always assume that the same economy-wide emissions target has to be met. *Differentiated* and *Thermal* represent policy scenarios that have been proposed by the Federal Council (2015*a*). 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_2 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_ETS* 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 *Optimal* scenario allows us to contrast the scenarios that reflect proposed Swiss carbon policies with a case which optimally differentiates carbon prices of motor and thermal fuels within the non-ETS sectors and chooses an optimal ETS cap to achieve a given reduction target at the lowest possible costs.

Our analysis assumes throughout that the revenues from CO_2 taxes are redistributed to households and industries. We follow here closely the redistribution scheme proposed by Swiss policy (Federal Council, 2015*a*) 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 recycled 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.[8]

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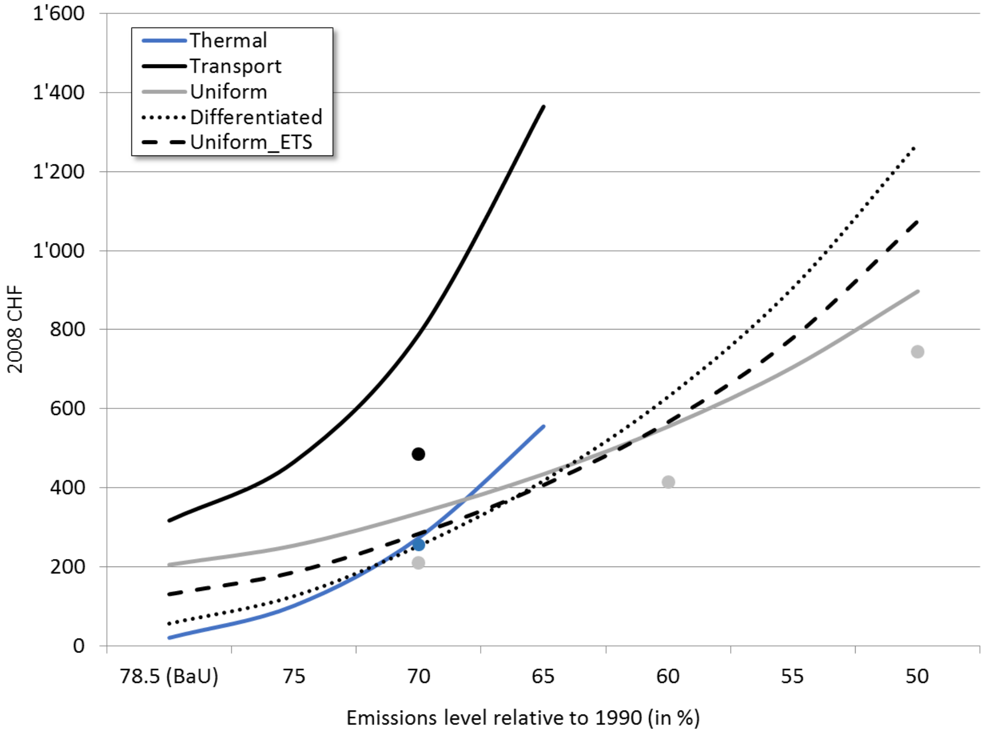
[8] We implicitly assume separability of public spending and private consumption in households' utility

Figure 2. Marginal welfare costs of abatement (lines) and CO_2 prices (dots) for alternative carbon pricing schemes



III. Carbon Tax Differentiation and Pre-existing Distortionary Taxes

In the discussion of results, we first focus on the case where the source for distortions in an otherwise efficiently running economy is the existing tax system. We compare total and marginal welfare abatement costs under optimally differentiated and previously proposed carbon pricing schemes. We also provide intuition for our efficiency results by analyzing fuel- and sector-specific CO_2 abatement patterns.

A. Marginal and total welfare abatement costs

MARGINAL WELFARE COSTS AND CO_2 PRICES.—When introducing CO_2 taxes in a first-best economy without pre-existing taxes and externalities, it is a well-established result that CO_2 prices correspond to marginal welfare costs (MWC) of

function, and refrain from modeling explicitly a public good. In this setting, any meaningful welfare analysis has to hold the level of real government spending fixed. Constant government spending is achieved by using a non-distortionary lumpsum tax instrument. The amount of carbon revenue that can be recycled to the economy is thus net of any tax base erosion effects that result from lower revenues of non-CO_2 taxes.

abatement and that uniform taxation of all CO_2 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_2 prices understate MWC of abatement (Bovenberg and Goulder, 1996). To develop an understanding of the quantitative importance of potential tax interaction effects in the Swiss economy, Figure 2 characterizes the marginal abatement costs and CO_2 prices associated with each carbon pricing scheme. 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. 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 the cheapest options for reducing fuel use.[9] Comparing MWC and corresponding CO_2 prices for the *Transport* scenario suggests a sizeable tax interaction effect that arises when imposing a CO_2 tax on motor fuels. For a 30% emissions reduction, the MWC costs are about 1.8 times larger than the CO_2 tax: 882 CHF/ton CO_2 (MWC) versus 485 CHF/ton (CO_2 tax). 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 278 CHF/ton CO_2 and the tax rate is 255 CHF/ton CO_2 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.[10]

Second, for sufficiently low emissions reductions, differentiating CO_2 prices between motor and thermal fuels yields significantly lower MWC. For example, for a 25% reduction, the MWC for *Uniform* are about 2.6 (2) times large than under *Thermal* (*Differentiated*). The MWC ranking, however, reverses for high abatement targets in excess of 35%: with an increasing stringency it becomes optimal 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 relatively 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_2 are lower than under the *Uniform* scenario as it is possi-

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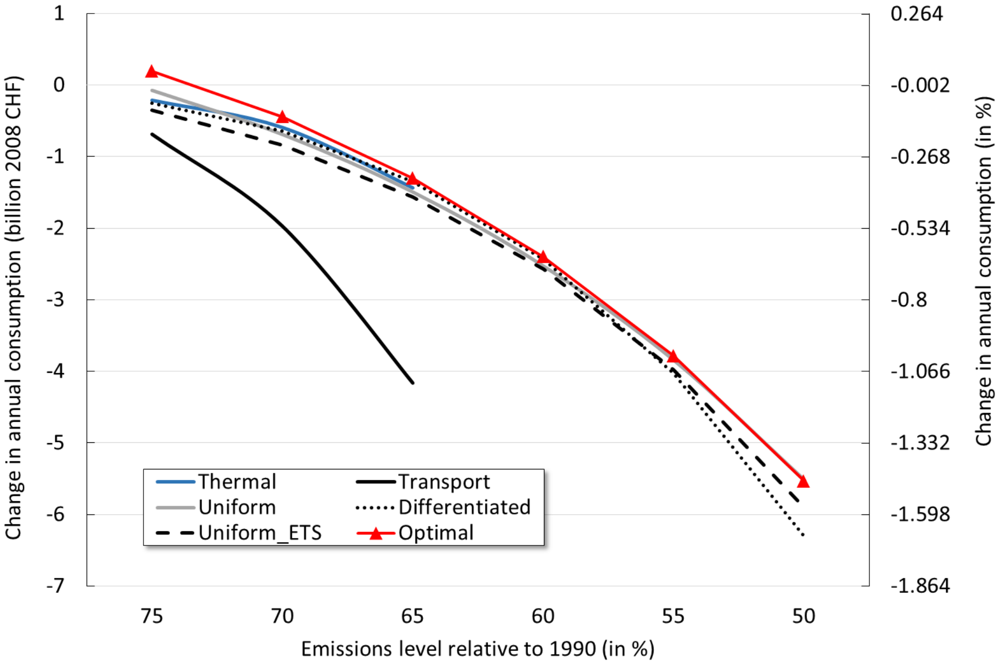
[9] While the magnitude of MWC difference between the transportation and non-transportation sectors depends of course on the specific technology assumptions for modelling the transportation sector, the finding that marginal abatement costs in the transportation sector tend to be relatively higher in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

[10] As of 2015, the mineral oil tax on motor fuels is 0.7422 CHF per litre while the tax on thermal fuels is only 0.003 CHF per litre.

Figure 3. Welfare costs of decarbonization for alternative pricing schemes (relative to BaU)



ble to exploit relatively cheap abatement opportunities 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., 40%) is optimal.

TOTAL WELFARE COSTS.—While a MWC perspective is useful to identify for which fuel there exist quantitatively important tax interaction effects, total welfare costs are what matters for deciding which policy option to adopt. Figure 3 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_2 emissions by 40% by 2030 (relative reduction to 1990 level)—which arguably seems to be in the range of the reductions targeted by current Swiss policy proposals—are about 0.4% of annual consumption or about 2.5 billion 2008 CHF 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

Table 3. Welfare cost difference relative to economy-wide uniform carbon pricing[a]

Emissions level[b]	*Transport* Δ	*Transport* %Δ	*Thermal* Δ	*Thermal* %Δ	*Differentiated* Δ	*Differentiated* %Δ	*Uniform_ETS* Δ	*Uniform_ETS* %Δ	*Optimal* Δ	*Optimal* %Δ
70	1.46	701	-0.15	-20	-0.08	-10	0.15	20	-0.30	-41
65	3.06	196	-0.14	-9	-0.20	-12	0.07	4	-0.29	-18
60	–	–	–	–	-0.14	-5	0.06	2	-0.29	-11
55	–	–	–	–	0.16	4	0.16	4	-0.29	-7
50	–	–	–	–	0.79	14	0.44	8	-0.30	-5

Notes: [a]Welfare cost difference measured as annual consumption loss in billion 2008 CHF. [b]Energy-related CO_2 emissions in % relative to 1990 level.

40% to 50% increases the annual welfare costs by a factor of three.

Figure 3 shows that the design of carbon pricing policies critically affects costs. 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 than three times larger than under any of the other scenarios for a 35% reduction).[11]

Table 3 compares the welfare costs of different carbon pricing schemes relative to the *Uniform* scenario which would minimize welfare costs in a first-best setting without pre-existing tax distortions. The suggestion that differentiating carbon prices across motor and thermal fuels can yield sizeable efficiency gains is borne out by the results in Table 3. The *Optimal* scenario indicates the maximum efficiency gains that can be obtained through carbon price differentiation (between motor and thermal fuels). Relative to uniform carbon pricing, optimally differentiating carbon taxes on motor and thermal fuels can yield up efficiency gains of up to 41%; 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 carbon tax structure proposed by Federal Council (2015*a*), brings about an efficiency increase of up to 12% relative to uniform emissions pricing. However, for reduction targets of 45% and higher, the proposed carbon tax policy would imply additional welfare costs. Finally, the scenario *Thermal* is almost as efficient as *Differentiated*.

B. *Optimally differentiated CO_2 taxes*

In order to identify the optimal level of carbon tax differentiation (the *Optimal* scenario), the contour lines in Figure 4 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_2 emissions by 40%. On the grid of analyzed policies, the smallest welfare loss is achieved by

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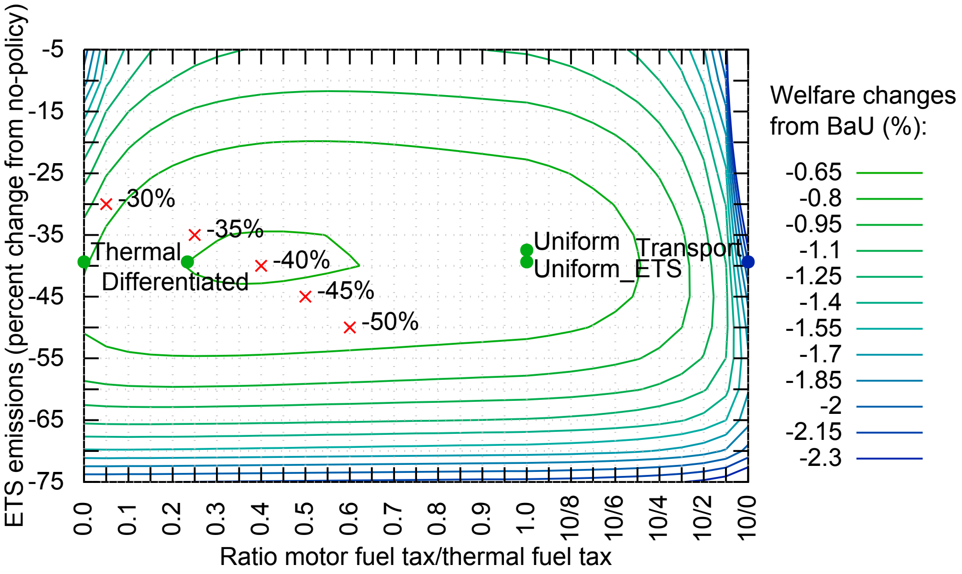
[11] Moreover, the numerical model failed to produce a solution for reaching reduction targets of 40% and higher in scenarios *Transport* or *Thermal*. While this does not rule out that a solution exists, it illustrates the difficulty of reaching the targets by taxing on fuel type only.

Figure 4. CO_2 tax differentiation between motor and thermal fuels for optimal and non-optimal carbon pricing schemes and alternative emissions reduction targets



Notes: The red crosses indicate the optimal tax differentiation (*Optimal* 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_2 taxes. The green dots locate non-optimal carbon pricing scenarios on the welfare loss surface.

an ETS cap that is 40% below no-policy emissions and a carbon tax on motor fuels that is 40% of the carbon tax on thermal fuels. We find the following points worth highlighting.

First, the optimal ratio of carbon taxes on motor and thermal fuels is significantly below one and varies substantially with the reduction target. For low reduction targets, it is optimal to almost not tax carbon embodied in motor fuels. This is due to the tax interaction effect stemming from the large mineral oil tax on motor fuels. With higher reduction targets, the optimal tax ratio increases but it remains markedly below unity even for ambitious reductions goals as high as 50%.

Second, among the non-optimal pricing scenarios, the tax ratio in the *Differentiated* scenario is the closest to the optimal policy design (for a 40% reduction target). This also means that the uniform emissions pricing scenarios (*Uniform* and *Uniform_ETS*) deviate substantially from the optimal tax differentiation across motor and thermal fuels.

Third, the currently proposed ETS cap approximately corresponds to a 40% reduction compared to our assumption about no-policy emissions and is well suited for reaching a cost-effective reduction of economy-wide emissions by 40%. This also explains why, for a 40% reduction target, the *Differentiated* scenario is almost as efficient as the *Optimal* scenario: it is relatively close to the optimal carbon pricing structure both in terms of differentiating CO_2 prices across the margins “ETS vs. non-ETS” and “thermal vs. motor fuels”.

Focusing on the welfare cost dimension (contour plots), Figure 4 provides another insight: Small mistakes in policy design (e.g., choosing *Differentiated* rather than *Optimal*) are significantly less severe in terms of efficiency losses as compared to fundamentally flawed policy designs (e.g., choosing *Thermal* or *Transport* instead of *Optimal*).

C. CO_2 emissions and fuel- and sector-specific abatement

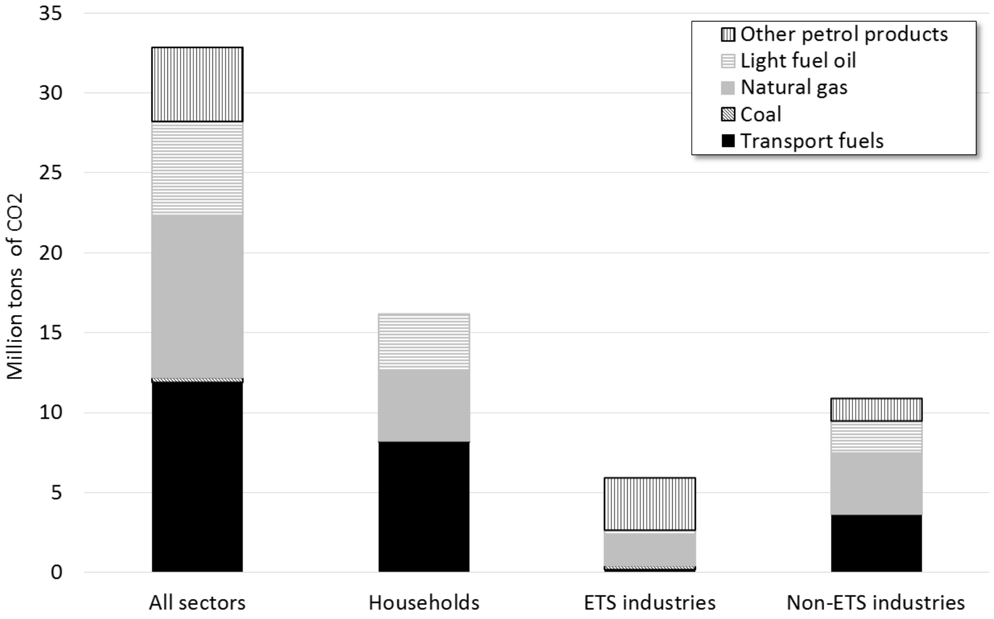
Figure 5a reports the CO_2 emissions by fuel and by end-use sector under the *BaU* reference scenario in 2030. About one half of CO_2 emissions stems from fossil energy use in the private household sector, the other half from industry use, with about 11 Mt CO_2 coming from non-ETS industries and 6 Mt CO_2 from ETS industries. In terms of fuels, the largest part of CO_2 emissions comes from motor fuels (36%), followed by gas (31%), light fuel oil (18%) and other petrol products (14%).

Figure 5b shows the reductions per fuel type and end-use sector for alternative carbon pricing schemes for a 40% reduction target. The triangles refer to the primary vertical axis and show the percentage change in emissions for the *Optimal* scenario relative to the *BaU*. Across all fuels, the largest percentage emissions reductions occur in the household sector and the non-ETS industries while emissions in the ETS industries are only slightly reduced (reflecting the near optimal cap of 40%, already present in the *BaU*, for an economy-wide reduction target of 40%). It is important to note that while transportation emissions are reduced somewhat in both household (−17%) and non-ETS sectors (−22%), the percentage reductions for all other, non-motor fuels are much larger.

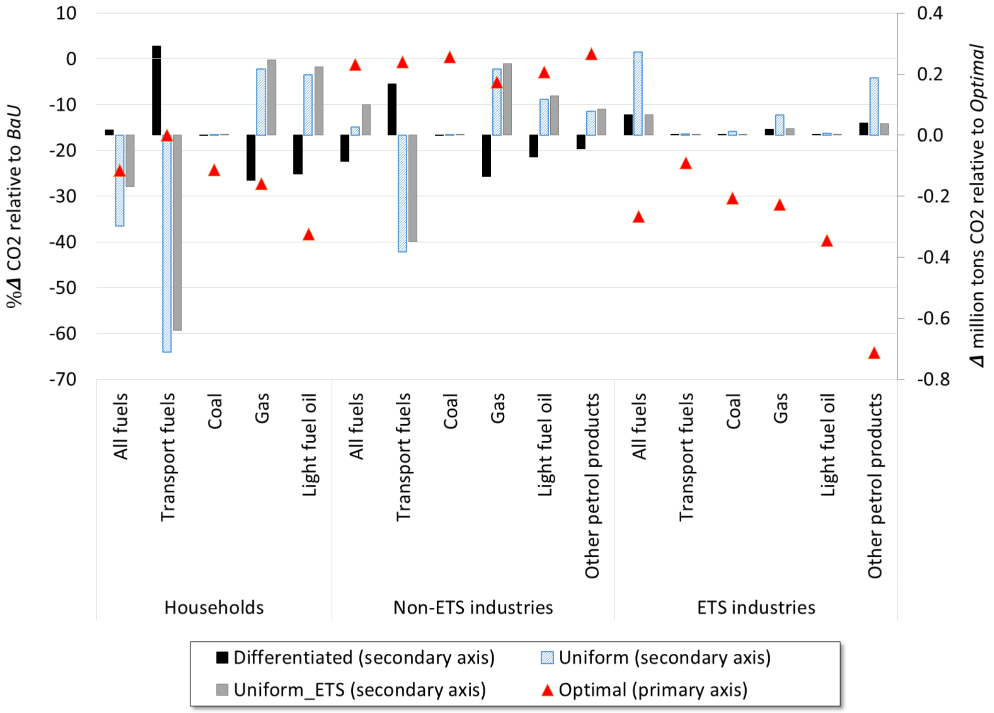
Two main insights emerge from comparing the pattern of emissions reductions among different carbon pricing schemes (shown by respective bars referring to the secondary vertical axis). First, the tax differentiation under *Differentiated* leads to a relatively similar abatement pattern as under optimal tax differentiation. The abatement pattern is virtually identical for the non-ETS industries. For the household and ETS sectors the biggest difference is that under *Differentiated* there is less abatement in motor fuels and more abatement in thermal fuels as the *Differentiated* assumes a lower motor-to-thermal fuel tax ratio as what would be obtained under *Optimal* tax differentiation (compare with Figure 4). Second, both scenarios with uniform emissions pricing (*Uniform* and *Uniform_ETS*) produce relatively large deviations from the optimal abatement pattern. In particular, they enforce sub-optimally high emissions abatement in motor fuels and too little abatement in thermal fuels.

Figure 5. CO_2 emissions by fuel and by end-use sector

(a) Business-as-usual CO_2 emissions in year 2030



(b) Change in CO_2 emissions for a 40% reduction target under alternative carbon pricing schemes



IV. Carbon Tax Differentiation and Distributional Impacts: Is There an Efficiency-Equity Tradeoff?

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.[12] 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.

A. Household expenditure and income patterns

Spending patterns in Switzerland agree with findings in other countries in that low income households spend the largest share of energy-related expenditures on heating and electricity while the high income households have the largest expenditure share for transport fuels. Figure 6a reports the energy-related annual expenditure shares for the income deciles of wage and salary earners and income quartiles of retired households in Switzerland. Expenditure shares for natural gas and electricity decline with income while expenditure shares for heating oil do not vary much with income. Expenditure shares for motor fuels are the highest for most households (with the exception of the two bottom quartiles of retired households) and increase with income. The uses side of income impacts of a carbon tax on thermal fuels are thus likely to be regressive while those of a carbon tax on motor fuels are likely to be progressive.

The overall incidence, however, also depends on the sources side of income impacts. Figure 6b points to the fact that there is substantial heterogeneity among household income groups with respect to their sources of income. In particular, the top income deciles for wage and salary earner 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.

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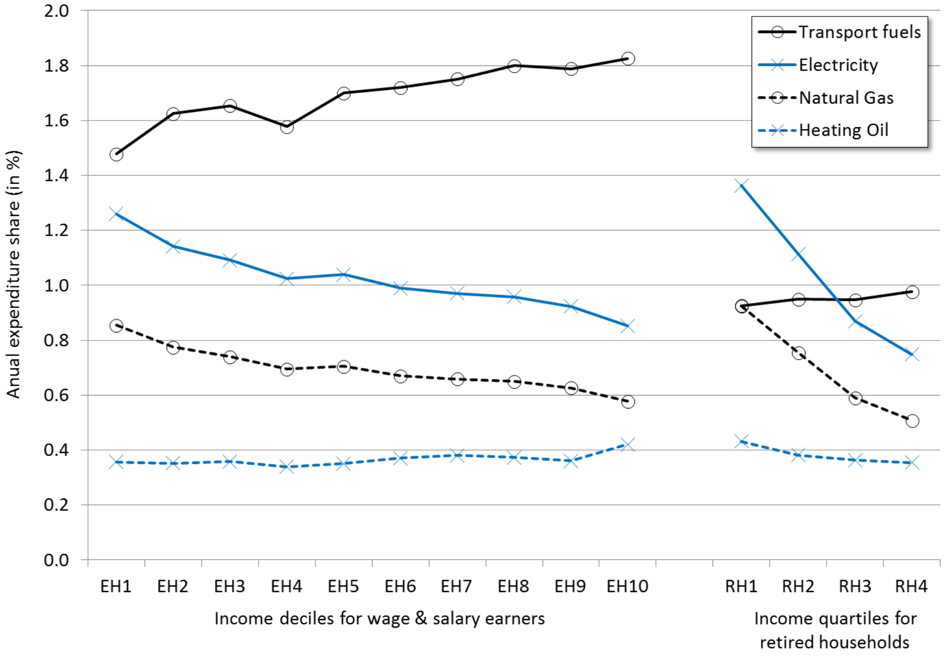
[12] Variation in impacts arise for, at least, three reasons. First, households differ in how they spend their income. Carbon pricing will raise the price of carbon-intensive commodities and disproportionately impact those households who spend larger than average shares of their income on these commodities. Second, carbon pricing also impacts factor prices. Households which rely heavily on income from factors whose factor prices fall relative to other factor prices will be adversely impacted. In the public finance literature on tax incidence, the first impact is referred to as a uses of income impact while the latter a sources of income impact (see, for example, Atkinson and Stiglitz, 1980). Third, the incidence of a carbon tax is also affected by the how the government returns the carbon revenue to the economy.

Figure 6. Energy-related expenditure shares and income shares by household income groups

(a) Energy-related expenditure shares



(b) Income share by source of income

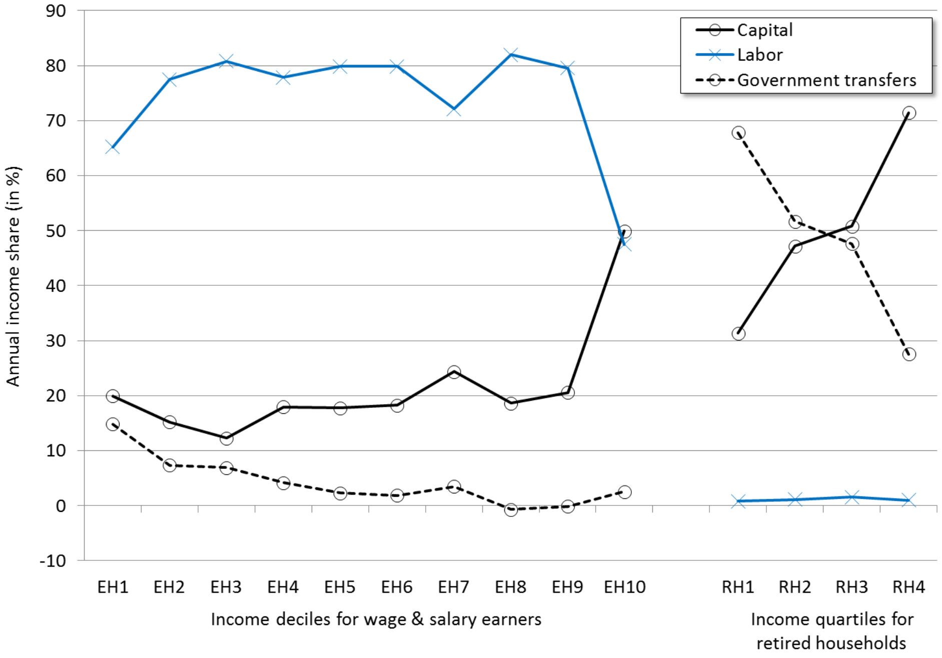
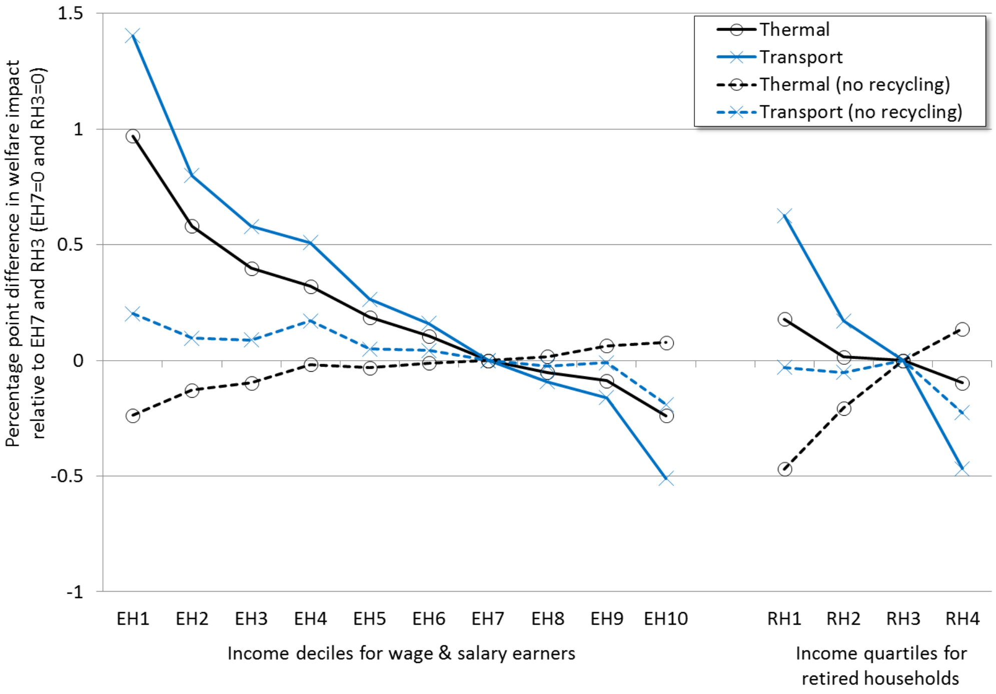


Figure 7. Normalized distribution of welfare impacts for carbon tax on only thermal or only motor fuels (for 35% emissions reductions)



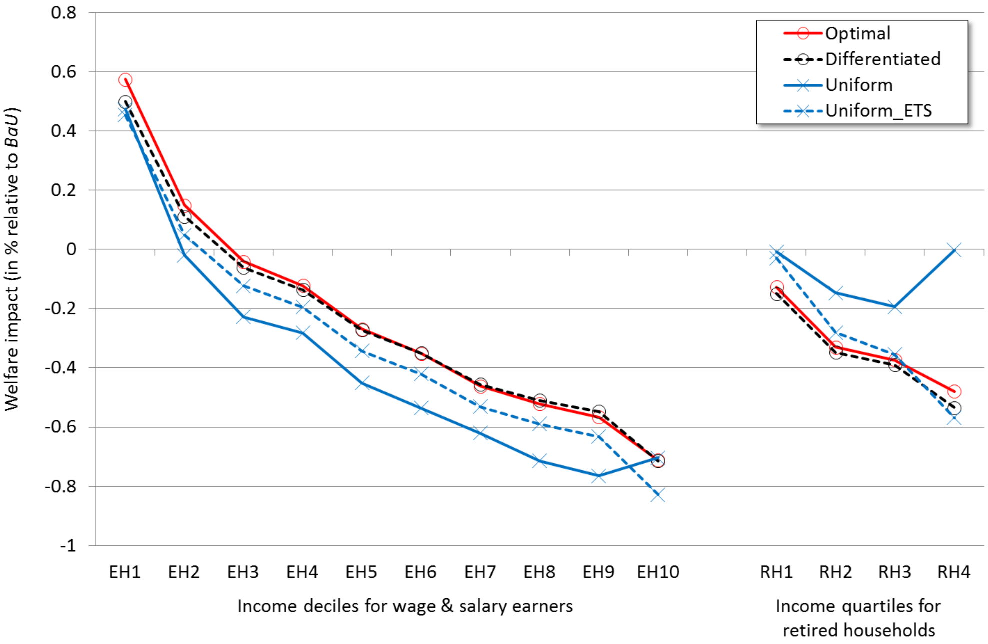
B. *Motor vs. thermal fuels*

Figure 7 shows the welfare impacts for each household income group for carbon pricing schemes that put a carbon tax on either motor fuels or thermal fuels. To focus on how distributional equity is affected, welfare impacts are normalized (relative to the respective middle income groups for both sets of households). We also report cases in which the carbon revenue is not returned back to households or the industry.[13] 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.

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 to almost neutral 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 returns to capital are absorbed more by high-income households which derive a relatively large share of income from capital. Redistributing the

[13] In this case, we assume that government spending is increased by an equal amount.

Figure 8. Welfare impacts for alternative carbon pricing schemes (for 35% emissions reductions)



carbon tax revenue on a per capita basis to households makes the overall tax incidence sharply progressive for both sets of households.

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

C. Mixed carbon pricing schemes

Neither taxing only thermal fuels nor taxing only motor fuels will achieve the ambitious CO_2 emissions reduction targets (i.e, 40% and higher) set out under Swiss climate policy at reasonable cost. Carbon pricing schemes are thus likely to eventually involve carbon taxes on both fuel categories.

Figure 8 shows the distributional welfare impacts relative to the *BaU* for the *Optimal*, *Differentiated*, and the two uniform carbon pricing schemes. While there are noticeable differences with respect to efficiency (as has been discussed above), it is important to note that the shape of the impact patterns is largely similar. The reason is that incidence results are dominated by the welfare impacts.

An important implication for policy is thus that the policy design in the context of differentiated carbon pricing should primarily focus on efficiency aspects and less on distributional equity.

V. Carbon Tax Differentiation in the Presence of Non-CO_2 Externalities of Motor Fuel Use

Our analysis has so far viewed all pre-existing taxes as distortions in an otherwise efficiently running economy. We have identified the pre-existing mineral oil tax as the reason to differentiate CO_2 taxes between different fuel types to improve over uniform emissions pricing. While one major purpose of the mineral oil tax is of course to raise revenue for road construction, road traffic has several non-climate related externalities such as, for example, local and global air pollution, noise pollution, traffic congestion, and traffic accidents (Calthrop and Proost, 1998; Parry, Walls and Harrington, 2006) which may be internalized through Pigouvian pricing (see, for example, Parry and Bento, 2002; Anas and Lindsey, 2011).

Such a Pigouvian tax would make transportation activities more expensive by the value of external damages these activities inflict on third parties through non-market based interactions. As our model does not consider such transportation externalities, our analysis so far may have misjudged the overall effects of alternative CO_2 tax differentiation schemes: while interactions with the mineral oil tax calls for a lower carbon tax on motor fuels, a higher carbon tax reduces transportation activities, in turn reducing non-CO_2 externalities.

A. *Social welfare function and empirical specification*

To gauge the importance of omitting such externalities, we define the social welfare function W in a way that includes utility derived from private market consumption and averted damages from non-CO_2 transportation externalities:

$$W(C_h, A_{\mathrm{motor}}) = \sum_h C_h - \beta(A_{\mathrm{motor}} - \bar{A}_{\mathrm{motor}}),$$

where A_{motor} is the activity level of motor fuel use in the Swiss economy, $\bar{A}_{\mathrm{motor}}$ its baseline level, and C_h is the purchasing power-adjusted consumption level of household h.[14] We moreover assume that welfare is separable in market consumption and the transportation externalities.[15]

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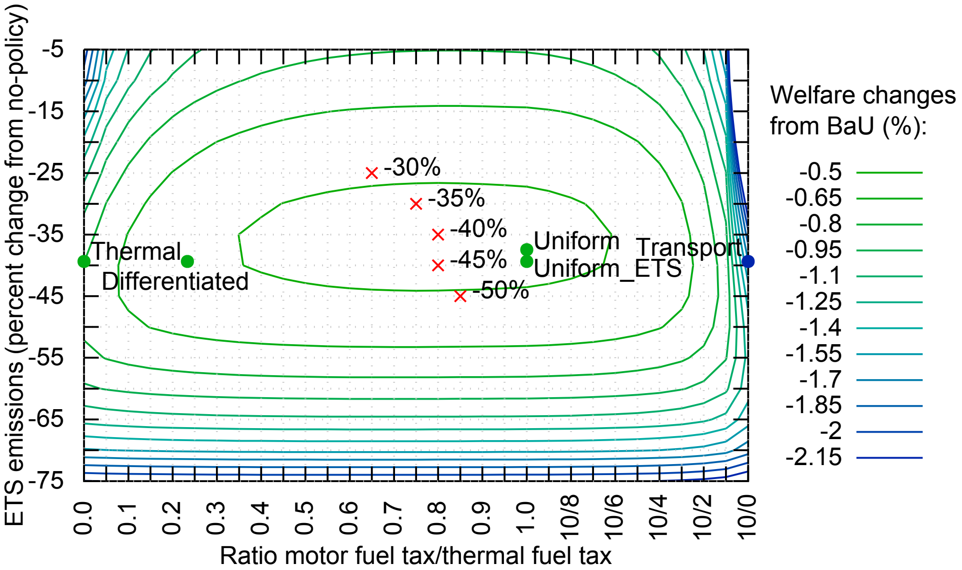
[14] This assumes that the marginal damages from the transportation externality is constant and that it is directly linked to fuel use. Both assumptions need to hold at least locally, if a Pigouvian tax on motor fuels that is not regularly adjusted is to be a reasonable policy measure to correct the externality.

[15] Of course, this is 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. Relaxing the assumption of separability would call for a more in-depth analysis which is beyond the scope of this paper.

Figure 9. Optimal tax differentiation between motor and thermal fuels in the presence of non-climate related transportation externalities



Notes: The red crosses indicate the optimal tax differentiation (*Optimal* scenario) for different emissions reduction targets. For a 40% emissions reduction, the green dots show the non-optimal carbon pricing schemes and the contour lines portray the corresponding welfare losses (relative to the *BaU*).

β denotes the marginal loss in welfare due to non-CO_2 related transportation externalities. What is an empirical plausible value for β? Existing studies indicate that the externalities caused by transportation are more than high enough to justify a Pigouvian tax of the magnitude of the mineral oil tax (ARE, 2014).[16] To avoid confounding the issue of setting the correct Pigouvian tax rate with questions about tax interactions, we assume that the mineral oil tax for 2030 indeed corresponds to the Pigouvian tax rate. We then calibrate β such that the marginal loss in welfare from transportation activities corresponds to the tax payments on fuel consumption by these activities.

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[16] A study of the Swiss Federal Office for Spatial Development (ARE, 2014) has shown that private transportation caused externalities (including traffic congestion, air pollution, climate-related costs, and others) of CHF 6.6 billion in 2010 of which 81.2 percent were not climate related. 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. This translates to externalities of about CHF 1.23 per liter of motor fuels which is well above the current level of the mineral oil tax. In 2010, new private vehicles in Switzerland on average carried 1.6 persons and used 6.4 liters of gasoline per kilometer (BFS, 2013*b*). Thus, private transportation delivers at least 25 person kilometers per liter of gasoline. The costs of non-CO_2 related transportation externalities can then be estimated to be about CHF 1.225 per liter of gasoline.

B. *Optimal carbon tax differentiation between thermal and motor fuels*

Figure 9 shows 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 optimal 10 tax differentiation (Optimal scenario) for different emissions reduction targets. For a 40% emissions reduction, the green dots show the non-optimal carbon pricing schemes and the contour lines portray the corresponding welfare losses (relative to the *BaU*).

Comparing Figure 9 with Figure 4 shows that even though the optimal differentiation of CO_2 taxes is much less pronounced than in the case which abstracts from transportation externalities, it does not vanish completely in the optimal setting. This is due to the previously identified tax interaction effect that causes marginal welfare costs of reducing an activity by taxing it in a second-best setting with pre-existing, distortionary taxes to be higher than the tax rate that one sets. The mineral oil tax that corresponds to the marginal damages of using fuels for transportation activities thus creates higher costs at the margin than the externalities that it avoids. The remaining optimal differentiation of CO_2 tax by fuels indicated in Figure 9 is compensating for this. With this policy design, CO_2 taxes are set at 382 CHF/ton CO_2 on motor fuels and 461 CHF/ton CO_2 on thermal fuels. The difference is now much smaller than the mineral oil tax (277 CHF/ton CO_2).

If policy makers are in disagreement if and to what extent non–carbon related taxes should price additional transportation externalities, our results suggest that a compromise that entails an intermediate level of carbon price differentiation would be acceptable if policy would otherwise have to choose between either uniform taxation or existing proposals for (non-optimal) differentiation. This can bee seen by comparing Figures 9 and 4. If transport externalities are not taken into account, Figure 9 suggests that the *Differentiated* policy design would be preferred over uniform carbon pricing schemes. If, on the other hand, transport externalities are taken into account, Figure 4 suggests that *Uniform* would be the preferable choice. An intermediate level of carbon price differentiation (e.g., around 0.6) could thus constitute an acceptable outcome for both sides as the regulatory costs would be quite close to those under previously preferred choices.

VI. Conclusion

This paper has analyzed 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, and heterogeneous households, we have assessed the empirical relevance of three motives for carbon price differentiation: fiscal interactions with the existing tax code, transportation externalities, and concerns about distributional equity.

We find that carbon tax differentiation may be beneficial. For the Swiss climate policy context, cost-effective carbon pricing policies entail substantially lower taxes on motor fuels than on thermal fuels (by a factor of 0.1–0.6). Non-optimal uniform carbon pricing forgoes sizeable efficiency gains on the order of 5–41% relative to optimally differentiated carbon taxes depending on the stringency of the climate policy. The main driver behind this result is a tax interaction effect that creates additional efficiency losses due to a “double” taxation of motor fuels through mineral oil and carbon taxes.

The case for carbon tax differentiation remains robust but is somewhat weakened if emissions reduction targets are large or if non-climate transportation externalities are taken into account. If policy makers are in disagreement if and to what extent non–carbon related taxes should price additional transportation externalities, our results suggest that a compromise that entails an intermediate level of carbon price differentiation would be acceptable if policy would otherwise have to choose between either uniform taxation or existing proposals for (non-optimal) differentiation.

We have not found evidence for a significant trade-off between efficiency and equity in choosing the level of differentiation between carbon taxes on motor and thermal fuels. This is because a carbon tax on motor fuels is more efficient than a carbon tax on thermal fuels while also leading to a more dispersed distributional outcome across household income groups. For carbon pricing schemes that involve taxing both motor and thermal fuels, distributional impacts are dominated by revenue recycling effects. An important implication for policy is thus that the policy design in the context of differentiated carbon pricing should primarily focus on efficiency aspects and less on distributional equity.

While our paper is one of the first to systematically analyze how carbon prices should be differentiated optimally in the presence of pre-existing taxes, several directions for future research appear to be fruitful. Firstly, in order to analyze the interactions between Pigouvian taxes and carbon prices, we interpreted the existing mineral oil tax as a Pigouvian tax introduced to correct the transportation externality. This approach serves well to highlight the continuing importance of tax interaction effects. A more policy-relevant way of treating transportation externalities would be to consider empirical estimates of the magnitude of these externalities rather than assuming the magnitude to be correctly represented by the existing mineral oil tax. The higher these estimated externalities, the weaker the case for carbon tax differentiation in favor of motor fuels if increasing the mineral oil tax is not an option. While being beyond the scope of this paper, a more explicit model of transportation externalities and their impact on private utility may yield additional insights.

Second, our focus of carbon tax differentiation between thermal and motor fuels was motivated by the Swiss policy context. A more finely differentiated carbon pricing, including, for example, various combinations of fuels, sectors, and end-users of energy, may arrive at different quantitative estimates with regards to the efficiency gains and distributional impacts from carbon tax differentiation.

Lastly, it may be interesting to explore to what extent our results would also carry over to other countries. The existence of high taxes on motor fuels, at least, for most of the European countries and the fact that household spending patterns for energy goods are relatively similar for industrialized, developed countries, however, suggests that our main insights would 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)[17] 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:

$$\text{(A1)} \qquad c_i^Y \geq (1 - to_i) r_i \qquad \perp \quad Y_i \geq 0 \qquad \forall i$$

$$\text{(A2)} \qquad c_{hh}^C \geq PC_{hh} \qquad \perp \quad C_{hh} \geq 0 \qquad \forall hh$$

$$\text{(A3)} \qquad c^G \geq PG \qquad \perp \quad G \geq 0$$

$$\text{(A4)} \qquad c^I \geq PI \qquad \perp \quad I \geq 0$$

$$\text{(A5)} \qquad c_i^A \geq PA_i \qquad \perp \quad A_i \geq 0 \qquad \forall i$$

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 1a, the unit cost functions for production activities are given as:

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

where

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[17] 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.

$$c_i^{TR} := \left[\sum_{j \in benz} \theta_{ji}^{TR} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{TR}} + \left(1 - \sum_{j \in benz} \theta_{ji}^{TR} \right) (c_i^{PUB})^{1-\sigma_i^{TR}} \right]^{\frac{1}{1-\sigma_i^{TR}}}$$

$$c_i^{PUB} := \left[\sum_{j \in pub} \theta_{ji}^{PUB} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{PUB}} \right]^{\frac{1}{1-\sigma_i^{PUB}}}$$

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

$$c_i^{MAT} := \left[\sum_{j \in mat} \theta_{ji}^{MAT} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{MAT}} \right]^{\frac{1}{1-\sigma_i^{MAT}}}$$

$$c_i^{VAE} := \left[\theta_i^{VAE} (c_i^{VA})^{1-\sigma_i^{VAE}} + \left(1 - \theta_i^{VAE} \right) (c_i^{EN})^{1-\sigma_i^{VAE}} \right]^{\frac{1}{1-\sigma_i^{VAE}}}$$

$$c_i^{VA} := \left[\theta_i^{VA} \left(\frac{(1+tl_i)PL}{\overline{pl_i}} \right)^{1-\sigma_i^{VA}} + \left(1 - \theta_i^{VA} \right) \left(\frac{(1+tk_i)PK}{\overline{pk_i}} \right)^{1-\sigma_i^{VA}} \right]^{\frac{1}{1-\sigma_i^{VA}}}$$

$$c_i^{EN} := \left[\sum_{j \in edt} \theta_{ji}^{EN} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{EN}} + \left(1 - \sum_{j \in edt} \theta_{ji}^{EN} \right) (c_i^{FF})^{1-\sigma_i^{EN}} \right]^{\frac{1}{1-\sigma_i^{EN}}}$$

$$c_i^{FF} := \left[\sum_{j \in coa} \theta_{ji}^{FF} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{FF}} + \left(1 - \sum_{j \in coa} \theta_{ji}^{FF} \right) (c_i^{LQ})^{1-\sigma_i^{FF}} \right]^{\frac{1}{1-\sigma_i^{FF}}}$$

$$c_i^{LQ} := \left[\sum_{j \in lqd} \theta_{ji}^{LQ} \left(\frac{PAS_j}{\overline{pas_j}} \right)^{1-\sigma_i^{LQ}} \right]^{\frac{1}{1-\sigma_i^{LQ}}}$$

θ refers to share parameters, σ denotes elasticicities 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 Aarmington 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[18], respectively, and ϕ_i the carbon coefficient. The price of non ETS industries addi-

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[18] 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.

tionally includes the mineral oil tax pmo_i. Hence, Armington prices for ETS and non ETS sectors are defined as:[19]

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

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:

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

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

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

According to the nesting structures shown in Figure 1b, the unit cost functions for production activities are given as:

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

where

---

[19] For ease of notation we suppress the fact that taxes and carbon coefficients are differentiated by agent.

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

For government and investment consumption fixed shares are assumed:

$$
\begin{aligned}
c^{G} &:= \sum_{i} \theta_{i}^{GTOP} \frac{PAS_i}{\overline{pas_i}} \\
c^{I} &:= \sum_{i} \theta_{i}^{ITOP} \frac{PAS_i}{\overline{pas_i}}
\end{aligned}
$$

Denoting each households initial endowments of labor and capital as $\overline{ls}_{hh}$ and $\overline{ks}_{hh}$, respectively, INC_{hh}^{C} and INC^{G} as consumer and government income and using Shephard's lemma, market clearing equations become:

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

$$\frac{\partial r_i}{\partial PD_i} Y_i \geq \frac{\partial c^A_i}{\partial PD_i} A_i \qquad \perp \quad PD_i \geq 0 \qquad \forall i \tag{A7}$$

$$\sum_{hh} \overline{ls}_{hh} \geq \sum_i \frac{\partial c_i}{\partial PL} Y_i \qquad \perp \quad PL \geq 0 \tag{A8}$$

$$\sum_{hh} \overline{ks}_{hh} \geq \sum_i \frac{\partial c_i}{\partial PK} Y_i \qquad \perp \quad PK \geq 0 \tag{A9}$$

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

$$C_{hh} \geq \frac{INC^C_{hh}}{PC_{hh}} \qquad \perp \quad PC_{hh} \geq 0 \qquad \forall hh \tag{A11}$$

$$G \geq \frac{INC^G}{PG} \qquad \perp \quad PG \geq 0 \tag{A12}$$

$$\sum_i \frac{\partial r_i}{\partial PFX} Y_i \geq \sum_i \frac{\partial c^A_i}{\partial PFX} A_i + \overline{bop} \qquad \perp \quad PFX \geq 0 \tag{A13}$$

$$e^{ETS}_{max} \geq \sum_i \phi^{ETS}_i \sum_{j \in ets} \frac{\partial c_j}{\partial PA_i} Y_j \qquad \perp \quad P^{ETS}_{CO_2} \geq 0 \tag{A14}$$

Carbon emissions of non ETS industries are given by:

$$\begin{aligned} E^{NETS} := \sum_i \phi^{NETS}_i \Bigg[\sum_{j \in nets} \frac{\partial c_j}{\partial PA_i} Y_j \\ + \sum_{hh} \frac{\partial c^C_{hh}}{\partial PA_i} C_{hh} + \frac{\partial c^G}{\partial PA_i} G + \frac{\partial c^I}{\partial PA_i} I \Bigg] \end{aligned} \tag{A15}$$

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:

$$
\begin{aligned}
\text{(A16)}\quad INC^C_{hh} :=\,& PL\overline{ls}_{hh} + PK\overline{ks}_{hh} - PI\bar{i}_{hh} - PC_{hh}\overline{htax}LSM \\
INC^G :=\,& \sum_i to_i \left(PD_i \frac{\partial r_i}{\partial PD_i} Y_i + PFX \frac{\partial r_i}{\partial PFX} Y_i \right) \\
&+ \sum_i ti_i PA_i \left[\sum_j \frac{\partial c_j}{\partial PA_i} Y_j + \frac{\partial c^C}{\partial PA_i} C + \frac{\partial c^G}{\partial PA_i} G + \frac{\partial c^I}{\partial PA_i} I \right] \\
&+ \sum_i tm_i PFX \frac{\partial c^A_i}{\partial PFX} A_i \\
&+ \sum_i Y_i \left[tlPL \frac{\partial c_i}{\partial PL} + tkPK \frac{\partial c_i}{\partial PK} \right] \\
&+ PC\overline{htax}LSM + PFX\overline{bop} \\
&+ p^{NETS}_{CO_2} E^{NETS} \\
&+ P^{ETS}_{CO_2} e^{ETS}_{max} \\
\text{(A17)}\quad &+ \sum_i \overline{pmo}\mu_i Y_i
\end{aligned}
$$

$\overline{htax}$ 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:

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

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
Sets	
$i \in I$	Commodities
$hh \in H$	Households
$ets \subset I$	Industries within the emission trading system (ETS)
$nets \subset I$	Non ETS Industries
$benz \subset I$	Gasoline ??
$publ \subset I$	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
Prices and quantities	
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
Elasticity of substitution parameters	
σ_i^{TOP}	Top level (transport vs. non transport inputs) in sector i
σ_i^{VA}	Value added composite in production sector i
σ_i^{VAE}	Value added vs. energy composite in production sector i
σ_i^{EN}	Energy composite in production sector i
σ_i^{FF}	Fossil fuel composite in production sector i
σ_i^{LQ}	Liquid fuel composite in production sector i
σ_i^{TR}	Transport composite in production sector i
σ_i^{NTR}	Non-Transport composite in production sector i
σ_i^{MAT}	Material composite in production sector i
σ_i^{PUB}	Public transport composite in production sector i
σ^{CTOP}	Top level consumption (transport vs. non transport)
σ^{CEN}	Energy composite in consumption
σ^{CFF}	Fossil fuel composite in consumption
σ^{CTR}	Transport composite in consumption
σ^{CNTR}	Non-Transport composite in consumption
σ^{CMAT}	Material composite in consumption
σ^{CPUB}	Public transport composite in consumption
σ^{CLQ}	Liquid fuel composite in consumption
σ_i^{T}	Elasticity of transformation between domestic and export markets
σ_i^{A}	Domestic vs. imported commodity i
Input and expenditure shares	
θ_{ji}^{TOP}	Share of commodity j in top-level production i
θ_{ji}^{TR}	Share commodity j cost in transport cost bundle
θ_{ji}^{PUB}	Shares of commodity j in public transport cost bundle
θ_{i}^{NTR}	Shares of material commodities in non transport cost bundle
θ_{ji}^{MAT}	Shares of commodity j in material cost bundle
θ_{i}^{VAE}	Share of value-added cost in value-added/energy cost bundle
θ_{i}^{VA}	Share of labor cost in value added cost bundle
θ_{ji}^{EN}	Share of commodity j cost in energy bundle
θ_{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
θ_{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
θ_{i}^{D}	Share of domestically supplied products
θ_{i}^{G}	Expenditure share commodity i in public consumption
θ_{i}^{I}	Expenditure share commodity i in investment consumption
Other parameters	
$\bar{i}_{hh}$	Reference investment level per household hh
$htax_{hh}$	Direct tax from household hh to government
e_{max}^{ETS}	Emission cap in ETS
ϕ_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
$p_{CO_2}^{NETS}$	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 (falsch!!!)
Production		
σ_i^{TOP}	Top level (transport vs. non transport inputs) in sector i	0.5
σ_i^{VA}	Value added composite in production sector i	0.5
σ_i^{VAE}	Value added vs. energy composite in production sector i	0.5
σ_i^{EN}	Energy composite in production sector i	0.5
σ_i^{FF}	Fossil fuel composite in production sector i	0.5
σ_i^{LQ}	Liquid fuel composite in production sector i	0.5
σ_i^{TR}	Transport composite in production sector i	0.5
σ_i^{NTR}	Non-Transport composite in production sector i	0.5
σ_i^{MAT}	Material composite in production sector i	0.5
σ_i^{PUB}	Public transport composite in production sector i	0.5
σ_i^{T}	Elasticity of transformation between domestic and export markets	0.5
σ_i^{A}	Domestic vs. imported commodity i	0.5
Consumption		
σ^{CTOP}	Top level consumption (transport vs. non transport)	0.5
σ^{CEN}	Energy composite in consumption	0.5
σ^{CFF}	Fossil fuel composite in consumption	0.5
σ^{CTR}	Transport composite in consumption	0.5
σ^{CNTR}	Non-Transport composite in consumption	0.5
σ^{CMAT}	Material composite in consumption	0.5
σ^{CPUB}	Public transport composite in consumption	0.5
σ^{CLQ}	Liquid fuel composite in consumption	0.5

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 (%Δ 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_2 emissions in ETS	-32.0