How Do Plants Respond to a Rising Carbon Tax? Empirical Evidence on Energy Consumption and Emissions

Dario Fauceglia *[1], Thomas Leu †[2], and Tobias Müller ‡[3]

[1]Zurich University of Applied Sciences & University of St. Gallen
[2]Zurich University of Applied Sciences
[3]Zurich University of Applied Sciences & University of Bern

February 21, 2019

Abstract

This paper examines how Swiss plants respond to a carbon tax that was increased by 400% during the period 2008-2015. In response to the tax and unrelated to sector affiliation, we find that while plants reduced carbon emissions by 12-15%, energy consumption fell by 4-6%. These results are consistent with a series of CO_2 fuel tax elasticities estimates ranging between -0.1 and -0.23. Plants in the service sector exclusively reduced emissions by consuming less fossil fuels, whereas plants in the industry sector also increasingly switched to the less carbon-intensive natural gas. Finally, more heavily taxed plants due to a relatively carbon-intensive energy mix as well as plants with high pre-policy emission levels decreased emissions disproportionately.

JEL Classification:

Keywords: Carbon taxes, plant behavior, emissions, energy consumption, tax elasticity

*Bahnhofplatz 12, 8400 Winterthur, Switzerland, email: dario.fauceglia@zhaw.ch
†Bahnhofplatz 12, 8400 Winterthur, Switzerland, email: thomas.leu@zhaw.ch
‡Corresponding author, Bahnhofplatz 12, 8400 Winterthur, Switzerland, email: tobias.mueller@zhaw.ch

1 Introduction

Global warming is one of the most fundamental and pressing challenges humankind is facing in present times. The rise in the global average temperature is predicted to intensify the occurrence of natural disasters and lead to a substantial increase in the sea level therefore posing a significant threat to the environment and ultimately to the welfare of entire societies. Carbon dioxide (CO_2) emissions accumulate over time in the atmosphere and are the main culprit for anthropogenic global warming (IPCC, 2013).[1] As a consequence, nations across the globe have started setting up joint initiatives since the early 90s to reduce the level of climate-damaging emissions and thereby counter the adverse long-term consequences of global warming. In the more recent Paris conference in 2015, nearly 200 countries agreed to limit the increase in the global average temperature well below 2° Celsius above pre-industrial levels.

There exists a broad consensus among economists that putting a price on carbon emissions either through the introduction of a tax or via emission trading systems is an efficient policy to reduce CO_2 emissions (e.g. Elkins & Baker, 2001; Arrow *et al.*, 1997). Nonetheless, 85% of current global emissions are not priced, including emissions from large emitting countries such as the United States (Stern & Stiglitz, 2017). This lack of a more widespread implementation of carbon pricing schemes may be explained by their low current political acceptability in the general public, in particular due to concerns about their efficiency and distributional effects (Klenert *et al.*, 2018). Despite the importance of this topic, the empirical evidence on the *ex-post* effects of carbon taxes on household and firm behavior remains scarce (e.g. Anderson, 2017; Martin *et al.*, 2014).[2] Additional research on its effectiveness may thus enhance the credibility and acceptability of carbon pricing and its subsequent implementation across a larger number of political entities.

In this paper, we study the impact of the introduction and increase of a carbon tax on the behavior of plants active in the service and industry sector in Switzerland. Using plant-level data for the years 2001-2015, we provide microeconometric evidence on how plants' energy consumption and carbon emissions respond to a rising carbon tax and thus contribute to a broader literature on the relationship between market-based climate policies and firm behavior (see, e.g., Metcalf, 2009; Fischer & Newell, 2008 for an overview). Our findings are highly relevant for policymakers as the industry and service sector account for about 40% of global CO_2 emissions (IEA, 2017). In terms of empirical scope and data, our study is most closely related to the work of Martin *et al.* (2014) who find significant reductions in the energy intensity and electricity use of plants after the introduction of the UK carbon tax in the early 2000s. A notable difference to their study is that in the Swiss setting we can empirically exploit the increase in the carbon tax of 400% between its introduction in 2008 and the year 2014. As a consequence, we are able to estimate fuel tax elasticities using the methodology suggested by Marion & Mühlegger (2008) and Li *et al.* (2014). In addition, we present novel insights about substitution patterns across energy sources as our data allows us to capture the carbon tax effect on plants' use of light oil, natural gas and electricity at the extensive (yes/no-decision about the

[1] Global CO_2 emissions reached a historic high of 32.5 gigatonnes (Gt) in 2017 (IEA, 2017).

[2] In contrast, the interplay between emission trading systems and firm behavior is better studied in the literature (e.g. Koch *et al.*, 2014; Aatola *et al.*, 2013; Betz & Sato, 2006).

use of a specific energy source) and the intensive margin (amount consumed). Lastly, we also contribute to a deeper understanding of the heterogeneous effects of the carbon tax across plants that differ in their sector affiliation, their pre-policy emission levels or tax exposure according to the carbon-intensity of their fossil fuel mix.

The main econometric challenge of this paper is to disentangle the effect of the carbon tax from changes in the economic activity, technological innovations and other policies affecting plant behavior. Our empirical strategy is three-fold: In a first step, we estimate the effect of the carbon tax while conditioning on plant characteristics, annual temperature patterns, business cycle indicators and energy prices. In contrast to simple pre-post analysis, we exploit the increasing treatment intensity of the tax over time, include plant fixed effects to account for time-invariant unobserved heterogeneity between entities and common time trends to absorb technological and policy innovations other than the carbon tax. This first approach provides within plant estimates of the carbon tax effect compared to pre-policy period after controlling for a wide set of time-varying covariates.

In a second step, we estimate various difference-in-difference specifications. Methodologically, this allows us to account for potentially unobserved time-varying confounders. The identifying assumption is that these confounders do not induce trends to diverge between treatment and control group. This is also known as the parallel trend assumption. In this framework, we exploit variation in the tax intensity plants face depending on the carbon-intensity of their pre-policy fossil fuel mix. As we find some weak evidence for violations of the parallel trend assumption in the "placebo" pre-policy period, we apply a tripple-difference procedure that removes the pre-policy effect from the diff-in-diff estimate in the policy period. In other specifications, we include plant-specific trends as a means of capturing diverging trends. In this case, the identification of the carbon tax effect hinges on whether this policy leads to deviations of plant emissions from plant-specific trends. More generally, while we extensively employ trends to capture innovations other than the carbon tax in many estimations, they are also likely to absorb some of the carbon tax effect that manifests itself in trend changes.[3] In addition, since reducing emissions requires substantial investments, the carbon tax effect is likely to unfold only gradually over time within plants. This exacerbates the problem of disentangling the carbon tax effect from underlying trend changes. We consequently interpret the results from specifications with plant-specific trends as *lower-bound* estimates of the differential carbon tax effect. Moreover, we take long differences of plant outcomes that encompass the entire policy (2008-2015) and placebo (2001-2008) period in some regressions in order to permit the carbon tax effect to grow over time among other reasons (see Section 5.1). In the estimations with annual data the likely gradual response of the carbon tax is taken into account by adding policy variables for each period with an increased tax level. These dummy indicators capture how the carbon tax effect accumulates over time in the policy period with respect to the baseline pre-policy period. In further regressions, we also use the fossil fuel mix in the beginning of the sample period to instrument the potentially endogenous fossil fuel mix in the beginning of the policy period. The concern is that plants might have adjusted their fossil fuel mix in anticipation to the future carbon tax policy. Reassuringly, the IV estimates provide almost identical results to OLS estimations in terms of magnitude and

[3] For example, the adoption of cleaner technologies or the use of subsidy programs induced by the carbon tax plausibly result in a downward shift in the emission trend at the plant-level.

statistical significance. In the last step, we confirm the importance of the carbon tax effect with estimations of the CO_2 fuel tax elasticities that are consistent with previous results.

Our results show that the carbon tax led to a cumulative reduction in the energy consumption by about 4-6% for the average plant in the post-policy period. In addition, our estimates indicate significant reductions in CO_2 emissions as a response to the tax: In particular, we find that the typical plant reduced emissions by about 2% upon introduction of the tax in the first policy period (2008-2009). With the subsequent increase in the tax, the effect increased to reductions between 3-6% in the second post-policy period (2010-2012) and up to 12-15% in the third post-policy period (2013-2015) relative to the pre-policy years. Given that the average pre-policy emission level was at approximately 610 tons of CO_2, the estimated policy effects are sizeable and imply cumulative reductions in the magnitude of about 70-90 tons of CO_2 for the average plant in the sample. Our estimates provide empirical evidence that the described emission reductions were mostly achieved by significant reductions in the consumption of both light oil and natural gas. However, this observation masks some substantial differences in how the emission reductions were achieved across sectors. Plants in the industry sector solely reduced light oil consumption (intensive margin) and increasingly started to substitute light oil with natural gas (extensive margin). In contrast, plants in the service sector uniformly reduced fuel consumption across both fuel types (intensive margin) without significantly switching to the less carbon-intensive natural gas (extensive margin).

We also assess whether plants with a carbon-intensive fossil fuel mix respond differently to the carbon tax than plants with a relatively low carbon-intensity. To this end, we compare plants which entirely relied on energy from light oil (treatment group) to those who exclusively used energy from natural gas (control group) as the tax burden for the former is substantially higher in the post-policy period. In our preferred tripple-difference specification with long differences, the higher tax burden of the pure light fuel users leads to emission savings of about 23% relative to pure natural gas users. In lower-bound estimates that use plant-specific trends instead of subsector-specific trends the difference between treatment and control group reduces to 7%. We also provide evidence that the emission reductions are primarily accomplished by plants with higher pre-policy emission levels (relative to the sector-median). Finally, our estimates of fuel tax elasticities are consistent with previous results overall. The tax elasticity for light oil ranges from -0.1 to -0.23, while the effect of the tax on natural gas is entirely driven by the service sector with an estimated elasticity of -0.17 in that sector.

Overall, our findings impart novel insights about the interplay between an increasing carbon tax and plant behavior along several important dimensions as we demonstrate their effectiveness in inducing plants to reduce their carbon dioxide emissions. Our results are relevant not only for the academic community but also for policymakers intended to design effective climate policy instruments in the near future.

The remainder of the paper is organized as follows. In Section 2, we describe the institutional background and the details about the Swiss carbon tax. Section 3 gives an overview of the data and key variables used to analyze the carbon tax effects. In Section 4, we discuss the effect of the carbon tax on various plant outcomes, while Section 5 presents difference-in-difference estimations. Next, we explore the heterogeneity of the carbon tax effect in Section 6 and provide tax elasticity estimates in Section 7. Section 8 concludes.

2 Institutional Background

2.1 The Swiss carbon tax

Under the Kyoto Protocol, Switzerland agreed to drastically reduce its green house gas (GHG) emissions. Specifically, Switzerland committed to reduce its GHG emission by 8% relative to the levels of 1990 in the first Kyoto commitment period between 2008-2012. In addition, the GHG reduction target was increased to 20% in the second, still ongoing, Kyoto commitment period between 2013-2020 (Federal Office for the Environment (FOEN), 2018). In order to reach these ambitious emission reduction goals, the Federal Act on the Reduction of CO_2 Emissions was enacted in 2008 by the Swiss parliament introducing three main climate policy instruments: the Swiss emission trading scheme (ETS), target agreements and most relevant for the majority of plants in the industry and service sector, a CO_2 levy on fossil fuels.[4] The CO_2 levy is a per unit tax on the CO_2 emissions stemming from the consumption of fossil fuels including heating oil, natural gas and coal.[5]

The initial level of the carbon tax was set at 12 Swiss Francs (henceforth CHF[6]) per ton of CO_2 emissions in 2008. Important for this study, the CO_2 Act stipulates tax increases if the predefined emission reductions are not met by the industry (Art. 94 of the CO_2 Act). In fact, the tax was raised in 2010 to 36 CHF, in 2014 to 60 CHF, in 2016 to 84 CHF and lately, it was further increased to a level of 96 CHF in 2018. In 2016, public revenues from the CO_2 levy amounted to 1.074 billion CHF: Around two thirds of the levy revenues are uniformly redistributed on an annual basis to all residents living in Switzerland and to the business community in proportion to their employees' social insurance contributions. One third of the revenue up to a maximum of CHF 450 million flows into the buildings program for energy efficiency improving renovations.

2.2 Tax burden under the Swiss carbon tax

Since the Swiss carbon tax is based on the amount of CO_2 emissions in tons, it varies substantially across different fossil fuel types depending on their carbon intensity. To illustrate this point, Table 1 below shows the tax burden by type of fossil fuel and Terajoule (henceforth TJ) of energy consumption over time. As clearly evident from the table, plants who are relying on energy from light oil face substantially higher taxes per TJ of energy consumed than those who mainly use energy from natural gas. Moreover, since the carbon tax was steadily increased over time to coincide with the predefined emission reduction path, the tax burden per ton of CO_2 emissions (i) rapidly increased over time and (ii) a growing wedge in the tax burden between light oil and natural gas can be observed rendering light oil consumption increasingly less attractive compared to natural gas. In numbers, while plants paid 885 CHF per TJ of energy from light oil in 2008-2009, the same amount of energy from natural gas resulted in 673 CHF in carbon taxes. Between 2010-2013 the tax burden per TJ increased to 2'654 CHF for light oil and 2'020 CHF

[4]The carbon tax is by far the most common policy instrument covering more than 95% of the companies active in Switzerland thereby defining our study population. Moreover, companies in the cement, chemicals, pharmaceuticals, steel, paper or district heating sector are exempted from the carbon tax and thus are excluded from our analysis.

[5]Note that motor fuels are not subject to the CO_2 levy but are instead subject to a separate petroleum tax.

[6]The average exchange rate in September 2018 was 1 CHF $\approx$ 0.88 Euro and 1 CHF $\approx$ 1.03 USD.

for natural gas. Finally, in the third post-policy period (2014-2016) when the carbon tax was increased to 60 CHF per ton of CO_2 emissions, the tax burden per TJ increased to 4'423 CHF for light oil and 3'366 for natural gas resulting in a tax differential of more than 1000 CHF for the same amount of energy consumed. From an economic point of view, the current carbon tax regime provides strong financial incentives to switch towards less carbon-intensive fossil fuels thereby affecting plant's current and future investment decisions which in turn will be reflected in their levels of CO_2 emissions.

— Insert Table 1 about here —

3 Data

We use plant-level data from the Swiss Federal Office of Energy for the years 2001-2015 (Bachmann *et al.*, 2014). The data set offers detailed information on plant's annual energy consumption and emission levels, as well as a series of plant characteristics including the number of employees, sector affiliation and floor size of the plant. We exclude plants from our analysis which are active in the (*i*) cement industry as the sector is exempted from the CO_2 levy[7] and (*ii*) plants which are only one year in the sample. Applying the described sample restrictions leaves us with an unbalanced panel of of 44'909 observations from 10'290 plants active in the industry (52.5%) and service sector (47.5%) between 2001-2015.

Figure 1 below shows the average annual energy consumption (in TJ) and CO_2 emissions (in tons) over time stratified by sector affiliation. *First*, the graph shows that the industry sector (dark blue line) with an average energy consumption of approximately 35 TJ clearly exceeds the one in the service sector (red line) of about 7 TJ. *Second*, in correspondence with the higher level of energy consumption, plants in the industry sector also produce substantially higher levels of CO_2 emissions: while the average plant in the industry sector emits on average about 950 tons of CO_2 per year, firms in the service sector release about 210 tons on average. *Third*, energy consumption and emission levels are fairly stable over time in the service sector. In contrast, the industry sector displays a comparably high variation in energy-related outcomes as captured by a substantially larger variance in both energy consumption and CO_2 emissions. Moreover and as a preliminary piece of evidence on the potential impact of the introduction of the carbon tax in 2008 (see vertical gray lines), Figure 1 indicates a slight negative trend in emissions in the post-policy period in the industry sector and essentially no change in emissions in the service sector – an observation we further explore in Section 6.1.

— Insert Figure 1 about here —

3.1 Pre-post policy descriptive analysis

To further motivate the upcoming *ex-post* policy analysis and provide additional information about our estimation sample, we present descriptive statistics for the pre-, as well as post-policy

[7]This restrictions drops 169 observations from the sample.

years in Table 2 below. The table gives detailed information about plant energy consumption for different energy sources including light heating oil, natural gas and electricity consumption. Note that the original data set also contains information about the consumption of heavy oil, natural wood, scrap wood and industrial waste. However, we refrain from using these additional energy sources as they account for only a negligible part of plant energy consumption.[8] Furthermore, we convert fossil fuel energy sources into their CO_2 equivalents in tons. In addition, we compute indicators for the share of light oil and natural gas in each plant's fossil fuel energy mix.

The pre-post mean comparison of the described outcomes shows that average plant energy consumption has slightly increased over time from roughly 21 to 22.5 TJ. Yet, the difference in means is not statistically significant thereby suggesting that the average plant did not systematically adjust the level of energy consumption over the observation window. However, the raw mean comparison shows a decrease of more than 20 tons of CO_2 emissions for the average plant in the sample. The key empirical question that arises in this context is whether this change in emissions can be attributed to the introduction of the carbon tax in 2008. Indeed, the raw pre-post mean comparison does not necessarily capture the causal effect of the policy as there are many possible channels which could plausibly explain the observed drop in emissions. For example, the decrease in emissions can at least partially be explained by the significantly lower economic growth that followed the financial crisis in 2008-09 and that persisted during the entire post-policy period.[9] Besides such macro shocks or comparable changes in the institutional setting which affected all plants in the economy, technological advancements or changes in plant characteristics more generally might have caused the emission levels to decrease. As we are going to describe further below in Section 4.1, conditioning on such macro- and plant-level factors is a key element in our identification strategy to isolate the effect of the carbon tax on plant outcomes. Finally, the pre-post mean comparison exercise provides evidence for substitution patterns among the different energy sources as we observe a significant increase in average natural gas consumption and at the same time a slightly smaller decrease in light oil consumption. In addition, there has been a remarkable increase (decrease) in the share of natural gas (light oil) in plants' fossil fuel mix, as shown in Figure 3 and Table 2. Interestingly, the shift from light oil to natural gas started already in the early 2000s and thus long before the introduction of the carbon tax.

— Insert Table 2 and Figure 3 about here —

To gain additional insights about the potential effects of the rising carbon tax on plant behavior and outcomes, Figure 2 below shows the distribution of total energy consumption, fossil fuel emissions, as well as light oil and natural gas consumption before and after the carbon tax was introduced. In line with the evidence from Table 2 above, the distribution of total energy consumption has shifted slightly to the right indicating a minor increase in plants' energy consumption post-policy. In contrast, the distribution of fossil fuel emissions has moved slightly to the left after the policy change as lower emission levels have become more likely. Moreover,

[8] For example, the share of heavy oil accounts for less than 1% in the average plants fossil fuel mix.

[9] Average annual real GDP growth was at a level of roughly 2.5% in the pre-policy period and only at 1.4% in the years after the introduction of the carbon tax.

Figure 2 indicates that plants tend to consume less light oil post-policy as depicted by the distinct shift of the distribution to the left, while lower levels of natural gas consumption have also gained in probability. In the following sections, we address the question of whether there is causal link between the carbon tax and plant outcomes.

— Insert Figure 2 and Figure 3 about here —

4 Carbon taxes and plant outcomes

4.1 Identification of the carbon tax effect

The main empirical goal of this paper is to estimate the effect of a time-varying carbon tax on plant energy consumption and emissions in the industry and service sector. As mentioned above, isolating a carbon tax effect is a challenge since multiple channels besides the carbon policy itself including, e.g., changes in the economic activity, energy prices, regulation and technological advances could potentially explain consumption and emissions patterns over time. We first estimate specifications that condition on plant characteristics, oil price, business cycle and weather indicators. Moreover and in contrast to simple pre-post analysis or event studies, our specification explicitly accounts for time-invariant unobserved plant heterogeneity by including plant fixed effects and absorbs technological progress and other preexisting trends by a linear time trend. In our second approach in Section 5, we exploit the implicit tax intensity that plants are exposed to depending on their fossil fuel mix. This additional variation across plants allows us to pick up potentially unobserved time-varying confounders within a difference-in-difference framework.

Specifically, in our first approach we capture the carbon tax effect by estimating the following fixed effects specification:

$$y_{it} = \tau_t D_t + x_{it}'\eta + A_t'\gamma + \lambda_i + \lambda t + \varepsilon_{it} \tag{1}$$

where y_{it} is an energy consumption/emission/fuel or electricity indicator for plant i in year t. To capture the effect of the increasing carbon tax, specification (1) includes a vector D_t that includes three treatment indicators each of which equaling one in the post-policy years in which the tax remained constant at the newly set level.[10] λ_i is a plant fixed effect capturing time-constant plant-specific factors such as a plant's short-term production technology or willingness to invest in, e.g., renewable energy sources. In addition, we include a linear time trend (t) to disentangle the carbon tax effects from common time-varying factors such as technological advancements and/or possibly other changes in the institutional setting.[11] Moreover, to isolate the carbon policy effect from observable plant-specific characteristics, we include in x_{it} the number of employees and the floor size as controls for plant size. Furthermore, we control for time-varying aggregate price, economic activity and weather indicators (in A_t).[12]

[10] Note that the baseline is given by the pre-policy years.

[11] As a robustness checks, we additionally estimate specifications with plant-specific time trends leading to both quantitatively and qualitatively similar results. The corresponding findings are available upon request.

[12] A_t includes an indicator for the number of heating degree days, GDP growth and an oil price index.

4.2 Carbon taxes and plant outcomes

Table 3 below presents the effect of the rising carbon tax on total plant energy consumption, emissions, light oil and natural gas consumption at the intensive and extensive margin.

Starting with energy consumption, we find that the introduction of the carbon tax shows essentially no impact on energy consumption in the first two post-policy periods until 2013. However, in the third post-policy period when the tax was increased to 60 CHF per ton of CO_2, our estimates show a significant decrease of about 4-6% relative to the pre-policy years indicating a lagged impact of the policy on plant behavior.[13]

Turning to carbon emissions, our estimates indicate increasing reductions in CO_2 emissions over time as a response to the carbon tax. In fact, we find evidence for significant emission reductions by about 2% after the introduction of the carbon tax in 2008-09. With the increase in the carbon tax, emissions further reduced by 3-6% in the second and between 12-15% in the third post-policy period. Based on the observation that the average pre-policy emission level was at a level of approximately 610 tons of CO_2 (see Table 2), the estimated policy effects are sizeable and imply cumulative reductions in the magnitude of 70-90 tons of CO_2 for the average plant 6-8 years after the introduction of the tax.

To visualize the previous results, the top panel in Figure 4 below depicts the counterfactual and actual evolution of average (log) energy consumption and emissions levels before and after the policy change.[14] As displayed in the upper left graph, the actual (solid line) and counterfactual (dashed line) energy consumption paths diverge in the final years of the policy period, implying that energy consumption levels would have been slightly higher in the third post-policy period in the absence of the tax. In contrast, the top right graph shows that CO_2 emissions would have been substantially higher in all three post-policy periods without the tax. Moreover, the effect of the tax on plant emission is increasing over time as the counterfactual and actual emission paths diverge over time.

A key question that arises at this point of the analysis is how the emission reductions were achieved. We thus address the following two questions: *a*) Does the carbon tax affect the plant decision to use specific energy sources? *b*) What is the carbon tax effect on the amount consumed of a specific energy source? To this end, we estimate the effect of the policy change on the consumption of light oil, natural gas and electricity both at the extensive and intensive margin (see Table 3 for details). Given the predominant trend away from light oil to natural gas consumption already starting in the early 2000s, the descriptive evidence in Figure 3 above suggests hardly any impact of the carbon tax on a plants' fossil fuel mix. Yet, our estimates imply that the carbon tax reinforced existing substitution trends in the fossil fuel mix as the probability of choosing light oil decreased by about 3-5 percentage points, while the propensity to opt for natural gas increased by roughly 1-2 percentage points.

[13] Although not disclosed in Table 3, the coefficient on the linear time trend is significantly negative as expected and captures arguably a general negative trend in consumption/emissions due to technological advancements and/or other institutional changes affecting plant outcomes across all specifications and outcomes.

[14] The counterfactual path is constructed based on the estimates from the described FE specification by switching off the policy indicators for all plants in the sample and subsequently generate predictions for each outcome for all post-policy periods.

At the intensive margin, both specifications provide evidence for an increasing negative impact of the rising carbon tax on light oil consumption. In particular, we find that the average plant in the sample significantly reduced the consumption of light oil by 3% in the first; between 7-10% in the second and up to 24% in the third post-policy period relative to pre-policy period. This implies sizeable reductions in light oil related emissions of 48-55 tons of CO_2 in the third post-policy period relative to pre-policy levels.

In contrast to the simple raw pre-post mean comparison, our estimates do not indicate an effect of the carbon tax on natural gas consumption in the first and second post-policy period. However, we estimate a significant negative effect of the carbon tax on natural gas consumption by about 10-14% or approximately 30-40 tons of CO_2 emissions when the carbon tax was increased to 60 Swiss Francs. Taken together, the overall reduction in CO_2 emissions of about 70-90 tons for the average plant in our sample can thus be explained by the reduction in both light oil and natural gas consumption.

The lower panels in Figure 4 further illustrate the estimated carbon tax effects on light oil and natural gas consumption. As shown in the lower left graph, light oil consumption would have been substantially higher in the absence of the carbon tax, in particular in the final years of the policy period. Similar conclusions can be drawn with respect to natural gas as the tax reduced the incentive to consume natural gas post-policy.

— Insert Table 3 and Figure 4 about here —

5 Tax intensity and plant emissions

5.1 Identification of the tax intensity effect

In a second step we estimate the differential effect of the carbon tax on plant emissions. Even though the tax per ton of CO_2 is the same for all plants in a given period (see Table 1), we exploit the fact that the (implicit) tax intensity increases with a plants' carbon emission intensity of its fossil fuel mix. More specifically, plants that use a higher share of light oil per unit of energy consumption are more exposed to the tax than plants relying more on the less carbon intensive natural gas. We therefore compare the emission patterns of plants that are confronted with different tax intensities in the following equation:

$$\Delta \ln (y_i) = \tau D_i + \Delta x_i' \eta + \lambda_s + \varepsilon_i \tag{2}$$

where $\Delta \ln(y_{it})$ denotes the change in the log plant emissions over the policy period 2008-2015 or the "placebo" period 2001-2008. D_i is either a dummy that equals one for pure light oil and zero for pure natural gas users[15]. In the policy-period $D_{i,2008}$ – measured in the beginning of the period in 2008 – captures a plant's degree of exposure to the carbon tax. Consequently, τ_{08-15} is an estimate of whether plants with a higher tax per unit of energy consumption reduce CO_2 emissions relatively more. Since we include subsector indicators λ_s in equation (2), identification of τ_{08-15} requires plant emissions to deviate from subsector trends. As above, we also control for

[15] Most plants in our sample rely exclusively on light oil or natural gas as their fossil fuel.

changes in floor size and number of employees in Δx_i. By measuring the cumulative effect on emissions with long differences Δ, equation (2) allows plant emissions to respond gradually to the CO_2 tax over time.[16] Moreover, equation (2) circumvents issues related to serially correlated errors and downward biased standard errors by ignoring the time series structure of the data, as suggested by Bertrand, Duflo and Mullainathan (2004). To purge τ_{08-15} from preexisting emission and substitution trends, as indicated in Figure 3, we subtract the placebo estimate τ_{01-08} from τ_{08-15}. The resulting $(\tau_{08-15} - \tau_{01-08})$ represents a tripple-difference estimate of the carbon tax policy and takes into account potential violations of the parallel trend assumption between plants that differ in their fossil fuel mix.[17] In further specifications, we instrument the tax-intensity measure in the beginning of the policy period 2008, $D_{i,2008}$, with its placebo period counterpart from 2001, $D_{i,2001}$, which is much less likely to be affected by plant responses to their fossil fuel mix in anticipation to the future carbon tax policy.

5.2 Results

Equation (2) is estimated in a balanced sample of plants that are present in our sample in the years 2001, 2008 and 2015. This results in a sample that contains between 367 (see columns 1 to 4 in Table 4) and 507 plants (columns 4 to 8), encompassing all major subsectors. We start by comparing the evolution of carbon emissions between pure light oil users (treatment group) and pure natural gas users (control group). One unit (TJ) of energy consumption from light oil is taxed about one third higher than an energy unit (TJ) sourced from natural gas, which reflects the same proportional difference in the carbon intensities of the two fossil fuels (see subsection 2.2 for details).

In column 1 of Table 4, we find that during the policy period between 2008 and 2015, plants that relied exclusively on light oil as their fossil fuel in 2008 ($D_{i,2008} = 1$), reduced their carbon emissions by about 30% by the end of the period relative to the emission path estimated for the average pure natural gas user ($D_{i,2008} = 0$). This result is not sensitive to replacing the 2008 (high tax) dummy for pure light oil users with its 2001 equivalent in column 2. Similarly, we instrument the (high tax) dummy 2008 with its 2001 counterpart, which does not alter magnitude and statistical significance of the diff-in-diff estimate in column 3. The Cragg-Donald F-statistics is above the Stock-Yogo critical value and thus indicates that weak identification is not a concern. This is also consistent with the fact that about 70% of the plants in the estimation sample do not adjust their fossil fuel mix between 2001 and 2008. However, we also note that there was already a small differential effect of the high tax dummy in the placebo period (2001- 2008), as can be seen from column (4). We therefore remove these diverging trends between pure light oil and natural gas users that predate the introduction of the carbon tax in 2008 by subtracting the placebo estimate τ_{01-08} in column (4) from the estimate τ_{08-15} taken from column (1). The difference between the two τ-estimates is -0.23 and statistically significant at the 0.01 level. This implies that pure light oil users reduced emissions by approximately 20% compared to pure natural gas users after taking preexisting background trends into account.

[16] This is likely to be important since changes in plant emissions usually require long-term investment such as building insulation that cannot be implemented over night.

[17] See Verhoogen (2008) for an application of this tripple-difference procedure in the field of international trade.

In the following specifications (4) to (8), we replace the previous binary treatment variable with a continuous tax intensity indicator measuring the share of light oil in the fossil fuel mix. This increases the sample size to 507 since there are plants using a combination of both fossil fuels (<30% of sample). The size and significance of the estimated coefficients are, however, not sensitive to this change and remain unaffected. Overall, the results in Table 4 provide evidence that plants that are exposed to a higher tax are more inclined to reduce carbon emissions than less heavily taxed plants. This is suggestive of a positive relationship between the tax burden and emission reductions consistent with economic intuition, in particular with an marginal abatement cost schedule that increases with lower levels of plant emissions.

— Insert Table 4 about here —

5.3 Robustness of the tax intensity effect

5.3.1 Econometric specifications

We check the robustness of the tax intensity effects by estimating a variant of equation (2) with our annual panel data. The new specification allows us to follow more accurately the evolution of carbon emissions for the treatment and control group over time. Specifically, the following equation will be estimated:

$$\ln(y_{it}) = \tau D_{it} + x'_{it}\beta + \phi_{st} + \lambda_i + \varepsilon_{it} \tag{3}$$

where $\ln(y_{it})$ denotes the log plant carbon emissions over time. As in equation (2), we control for plant size changes over time in x_{it}. We also pick up technological, regulatory or demand shocks with subsector-year fixed effects, ϕ_{st}.[18] As in equation 2, we divide the sample into high tax (share light oil=1) and low tax plants (share light oil=0) according to plants' pre-policy fossil fuel mix.[19] To obtain the final D_{it} in equation (3), we interact the high tax dummy with treatment indicators in the vector D_t (see equation (1)) that tag the three tax regime periods with constant tax levels.[20]

In the next step, we also include plant-specific trends to permit treatment selection on differential trends. For example, light fuel consumers may be more inclined to reduce carbon emissions over time than natural gas users for reasons other than the carbon tax, as suggested in Figure 3. Consequently, we have an equation in mind that controls for differences in emission levels with plant-specific fixed effects (λ_i), trends ($\lambda_i t$) and year fixed effects (ϕ_t) as follows:

$$ln(y_{it}) = \tau D_{it} + x'_{it}\beta + \phi_t + \lambda_i + \lambda_i t + \varepsilon_{it} \tag{4}$$

[18] They are intended to capture macroeconomic shocks, as well as energy saving and policy innovations such as the subsidy programs for renewable energy sources or building insulation.

[19] We only considered plants with a constant pre-policy fossil fuel mix, which applies to the large majority of plants.

[20] 12 CHF per ton of CO2 from 2008 to 2009, 36 CHF per ton of CO2 from 2010 to 2013 and 60 CHF per ton of CO2 from 2014 to 2015.

In practice, equation (3) is most easily empirically implemented by taking first differences over time as follows:

$$\Delta ln(y_{it}) = \tau \Delta D_{it} + \Delta x'_{it}\beta + \lambda_i + \lambda_t + \Delta\varepsilon_{it} \tag{5}$$

where $\lambda_t = \phi_t - \phi_{t-1} =$ is a new set of time fixed effects. In equation (5), the plant fixed effect $\lambda_i = \lambda_i t - \lambda_i(t-1)$ captures linear plant-specific trends, as discussed above (Wooldridge, 2010).

Finally, we also employ a continuous plant-specific tax intensity measure that is weighted by the fossil fuel mix. Specifically, we define a new continuous policy variable $D_{it} = ln(\sum_{i=1}^{2} w_i \times tax_{it})$, with the weight w_1 corresponding to the average plant's share of light fuel consumption in the pre-policy period, and $w_2 = 1 - w_1$ to the share of natural gas consumption. These shares are multiplied by the fuel-specific tax (tax_{it}) and summed over both fossil fuel alternatives to obtain a tax per TJ energy consumption faced by each plant.

5.3.2 Results

The treatment effect is increasing in the level of the carbon tax across, as visible in the first column of Table 5. The estimates in the first specification including plant fixed effects and subsector-year fixed effects suggest that carbon emissions of the pure light oil users would have been 11% higher in the absence of the higher tax intensity when the carbon tax was at a level of 36 CHF per ton of CO_2 and 13% higher at a tax level of 60 CHF. In line with our expectations, the magnitude and statistical significance of the carbon tax effect is reduced when we add plant-specific trends to the specification in column (2). This indicates that some of the carbon tax effect manifests itself in trend changes that are potentially plant-specific and predate the carbon tax introduction. This interpretation is also supported by the results in column (2) in which we find that the *High Tax* dummy turns out to be weakly significant with a small magnitude in both pre-policy "placebo" periods 2006-2007 and 2004-2005. We encountered a very similar result with the long difference estimates in column 4 and 8 of Table 4 that displayed a differential change in emissions between plants that differ in their carbon-intensity already in the placebo period 2001-2008 (see subsection 5.2). Once we include plant-specific trends in column (4) of Table 5, the *High Tax* dummies for the two placebo periods (2006-2007 and 2004-2005) become insignificant and their previous effect on plant emissions rightly attributed to trend or absorbed by the year fixed effects. Column (4) also reveals a significantly reduced magnitude and significance of the tax intensity effects, therefore some of the previous post-policy carbon tax effects visible in column (4) may have been absorbed by the plant-specific trends. Overall, it is reassuring to see that the estimates with the annual data in Table 5 are comparable to previous estimates obtained with the long difference specification in equation (2) (see Table 4).

We also provide first empirical estimates of the tax elasticity of emissions based on our continuous plant tax measure per TJ of energy consumption. Note that the estimates are exclusively based on the post-policy sample as the tax was only introduced in 2008. Overall, our estimates suggest a significant negative relationship between the plant-specific tax and subsequent carbon emissions in columns 5 and 6 of Table 5. To be more precise, we find that the tax elasticity of emissions ranges between 0.18 with plant-specific trends (see column 6) and -0.34 with subsector-year fixed effects but without plant-specific trends (see column 5). This indicates that a 1% increase in the carbon tax is associated with a decrease in CO_2 emissions of -0.18% at the minimum. Using simple back-of-the-envelope calculations, applying the lower bound tax elasticity estimate implies for example that the increase in the carbon tax between the second and the third post-policy period from 36 CHF to 60 CHF (i.e. Δtax =+ 66.67%) is associated to decrease CO_2 emissions by roughly 12%, which is in line with our earlier lower-bound estimates of the policy effect in Table 3 of Section 4.2.

In the final two columns of Table 5, we replace the log carbon emissions by log electricity consumption as the dependent variable. Since electricity in Switzerland originates mainly from renewable energy sources such as water or wind, it is not subject to a carbon tax.[21] As a consequence, the introduction of the carbon tax should not directly affect electricity consumption (placebo test). Indirectly, plants might partly substitute fossil fuels with electricity. We thus expect insignificant or positive policy estimates with electricity as the dependent variable. Consistent with our expectations, we find weakly significant positive estimates in columns (7) and (8). This may also indicate substitution patterns away from fossil fuels towards electricity.

— Insert Table 5 about here —

6 Heterogeneous effects of the carbon tax

6.1 Effect heterogeneity by sector affiliation

In this section, we explore the potential heterogeneity in response to the introduction of the carbon tax between plants in the industry and service sector. As indicated in Figure 1 above, the graphical evidence suggests that while both total energy consumption and emissions are essentially constant over time in the service sector, the opposite is true for the industry sector as consumption/emissions display a considerable level of volatility. At least part of the persistency in the service sector can be explained by the simple fact that most firms in the service sector are renting their office spaces in buildings they do not own themselves and therefore usually have less influence on, e.g., the heating technology used in the corresponding building. From this line of thinking, it follows that one would naturally expect a smaller response to the carbon tax in the service than the industry sector. To empirically assess such hypothesis, we re-estimate our fixed effects specifications from above in the sub-sample of plants in the service and industry sector separately. The corresponding results are summarized in Table 6 below.

As for the total energy consumption, our estimates indicate no impact of the carbon tax on total consumption in the first two post-policy periods in both the industry and service sector. In correspondence with the full sample estimates above, our estimates show significant reductions in total energy consumption of about 4-5% relative to the pre-policy era in the third post-policy period in both sectors providing evidence for a homogeneous response to the carbon tax. In correspondence to this result, we do not find evidence for systematic heterogeneity between the two sectors in their response to the carbon tax on their CO_2 emissions as the policy effects are practically identical in magnitude. Specifically, the average plant in both sectors tends to

[21] In addition, imported electricity was less heavily taxed by the European emission trading scheme during the policy period

decrease emissions by approximately 6% in the years when the levy was increased to 36 CHF per ton of emissions and 13% in the third post-policy period. Indeed, given the substantially higher average level of emissions in the industry sector of about 960 tons of CO_2 prior to the introduction of the carbon tax, the cumulative emission reductions amount to roughly 125 tons of CO_2 in the third post-policy period for the typical plant in the industry sector thereby clearly exceeding the one in the service sector of about 30 tons.[22]

Furthermore, the next blocks of estimates provide evidence for substantial effect heterogeneity between the two sectors as we find sharp and significant reductions in the propensity to opt for light oil, as well as on the amount consumed: while the negative response of plants in the industry sector intensifies over time both at the intensive and extensive margin, plants in the service sector solely tend to significantly reduce light oil consumption in the third post-policy period. In numbers, while the average plant in the industry sector reduces light fuel consumption by about 6% in the first post-policy period, the response to the increasing carbon tax increases to reduction levels of about 15% in the second and 26% in the third post-policy period. Similarly, the likelihood of opting for light oil significantly decreases by 2 percentage points in the second and 4 percentage points in the third post-policy period exclusively in the industry sector.

In sharp contrast, our estimates indicate a strong negative and increasing impact of the carbon tax on natural gas consumption in the service sector but no effect whatsoever in the industry sector. Yet, further heterogeneity can be observed between the two sectors as solely plants in the industry sector tend to significantly increase the likelihood of opting for natural gas as a response to the tax indicating that the above described substitution of light oil with natural gas is driven by plants active in the industry sector.

In conclusion, the introduction of the carbon tax indeed lead to the described overall reductions in CO_2 emissions in both sectors but while the typical plant in the industry sector achieved the reductions by cutting back on light oil or by switching to natural gas, the average plant in the service sector reduced emissions by mostly burning less of both fossil fuels.

— Insert Table 6 about here —

6.2 Effect heterogeneity by pre-policy emission-level

In this section, we examine whether plants with emissions above the (pre-policy) median level in their subsectors tend to display higher emission reductions relative to plants with below-median levels of emissions. Theoretically, such a heterogeneous patterns of emission reductions could be explained by marginal abatement costs that are inversely related to the level of plant emissions within a respective subsector. In column (1) and (2) of Table 7 we start by estimating a long difference specification as in equation (2) that contrasts plants with above median levels of emissions with those exhibiting below median levels of emissions. Columns (1) shows that plants with above-median emissions in 2008 *(High emission (in 2008))* subsequently decreased their emissions in the policy period relative to plants with below-median emission levels. We

[22] Note that since the sample contains roughly a 50-50 mix of plants in both sectors, our estimates imply an overall reduction in emissions of about 70-90 tons for the average plant in the sample thus closely resembling our main findings from above. (see Section 4.2)

find in column (2) that high emission plants tended to reduce emissions in comparison to the control group already in the pre-policy period from 2001 to 2008. We remove these background trends related to emission levels by subtracting the estimate of the *High emission (in 2001)* dummy (see column 2) from the *High emission (in 2008)* dummy estimated in column (1). This difference of -0.14 is statistically significant at the 0.05 level and suggests that there is carbon tax-driven positive relationship between the pre-policy level of plant emissions and the subsequent extent of emission reductions during the policy years.

We turn next to estimating equation (1) with our annual panel data in order to study the reaction of plant emissions, total energy consumption and the consumption of both light oil and natural gas. Confirming previous results from Table 3 in Section 4.2, we find that the average plant emissions fall in the post-policy years, which materialized through reductions in both light oil and natural gas (see columns 3 to 8). A new insight is, however, that these reductions in plant emissions and fossil fuel consumption were mainly achieved by plants with above-median levels of emission, as revealed by comparing columns (3) to (4) , (5) to (6) and (7) to (8). In addition, we also see in columns (7) and (8) that the reduction in total energy consumption that can be attributed to the carbon tax according to Table 3 in Section 4.2 is again driven foremost by plants with higher than median-level emissions.

— Insert Table 7 about here —

7 The elasticity of the carbon tax

In this section, we disentangle the reaction of plants to CO_2 tax changes from reactions due to changes in prices of fossil fuels (i.e. light oil and natural gas) net of CO_2 taxes. This allows us to provide a fuel-specific estimate of the tax elasticity following the decomposition methodology proposed by Marion & Mühlegger (2008) and Li *et al.* (2014).

7.1 Econometric equation and derivation of the tax elasticity

We start by rewriting the tax-inclusive gross price p^B as the sum of the net price p_t and the tax per unit of fossil fuel T (1 kw natural gas or 100 liter heating light oil); $p^B = p + T$. By factoring out the net price and taking logs, we decompose the gross price into a tax-exclusive net price and a tax-inclusive component ; $\ln(p^B) = \ln(p) + \ln(1 + \frac{T}{p})$. This decomposition forms the basis for the following equation:

$$\ln(y_{it}) = \alpha \ln(p_t) + \beta \ln\left(1 + \frac{T_t}{p_t}\right) + x'_{it}\eta + A'_t\gamma + \lambda_i + \lambda t + \varepsilon_{it} \tag{6}$$

, where $\ln(y_{it})$ denotes plant consumption of light oil or natural gas. Importantly, equation (6) includes $\ln(p_t)$ and $\ln(1 + \frac{T_t}{p_t})$ as separate regressors in order to derive the tax elasticities from the corresponding estimated β coefficient. Following equation (1), we include a aggregate linear time trend t intended to capture technological and institutional developments in all estimations. In the most rigorous estimates we employ the identical set of control variables and plant fixed effects to equation (1). More controversially, we rely on OLS estimates to obtain the coefficients for the elasticity calculations. Given its relatively small size Switzerland can be regarded as a price taker that does not affect world market prices of fossil fuels. Moreover, we also control for annual temperature patterns and for the business cycle in order to absorb potential demand-driven adjustments of local fossil fuel prices. As a result, fossil fuel prices are assumed to be exogenous from the viewpoint of operating plants, at least after controlling for local weather and economic conditions. We also care about the greater precision of OLS estimates for the elasticity derivation compared to less precise IV estimates.

As mentioned above, the tax elasticity is related to the estimated β coefficient. We can first take the derivative of equation (6) with respect to CO_2 tax to obtain the following semi-elasticity, $\frac{\partial \ln(y)}{\partial T} = \beta \frac{1}{p+T}$, which is the percent change in fuel consumption associated with a unit increase in the CO_2 tax. This semi-elasticity must be multiplied by the tax to arrive to the final CO_2 tax elasticity:

$$\frac{\partial \ln(y)}{\partial T} T = \frac{\partial \ln(y)}{\partial \ln T} = \beta \frac{T}{p+T} \tag{7}$$

This derivation of the tax elasticity holds under the assumption that taxes do not influence net prices of fossil fuels, that is $\frac{\partial p}{\partial T} = 0$. In other words, CO_2 taxes must be fully passed on to consumers, which corresponds to a complete pass-through of the CO_2 tax to gross prices. Due to the short tax series, we are not able to test this assumption empirically. However, an exogenously fixed world market price for fossil fuels for Swiss consumers would imply that CO_2 taxes are fully borne by domestic consumers. In addition, Marion & Mühlegger (2011) and Li *et al.* (2014) provide evidence for a rapidly achieved full pass-through of fuel taxes in the US, which is responsible for a much larger share of world demand for fossil fuels than Switzerland.

7.2 Elasticity estimates

We present the estimated results of equation (6) in Table 8. Consistent with Li *et al.* (2014), we observe that plants tend to respond more strongly to the tax than than to the tax-exclusive net price, as the magnitude of the estimated β (second row) is mostly significantly larger than the α estimate (first row). [23] An explanation might be that plants regard the CO_2 tax as permanent as opposed to fossil fuel prices that exhibit a substantial amount of "natural" variation over time. This can be seen from Figure 5 that plots the gross and net prices of heating light oil (upper panel) and natural gas (lower panel) over time. The price charts are complemented with volatility bands calculated by an exponentially weighted moving average method and displayed as shaded areas around the price lines. This volatility measure is quite large and may reflect the consumer believe of mostly transitory fuel price movements, while the CO_2 tax may be anticipated to be permanent and to increase over time. Moreover, we also find from columns (5) and (6) that the effect of the tax on light oil consumption does not differ across sectors. We employ the tax elasticity of light oil from equation (7) to the estimated β's in specifications (1) and (2). Accordingly, we require a value for the share of the CO_2 tax in the net price ($\frac{T}{p+T}$) to

[23] This can be seen by taking the derivative of equation (6) with respect to the tax-exclusive net price and obtain the following price semi-elasticity: $\frac{1}{p}(\alpha - \beta \frac{T}{p+T})$. The tax semi-elasticity $\beta \frac{1}{p+T}$ is larger than the price semi-elasticity whenever $\beta > \alpha$ applies.

calculate this elasticity. This tax fraction of the overall oil net price rose from 3% in 2008 to about 20% in 2015 and thereby inducing plants to respond more strongly to the tax, as reflected in an increasing tax elasticity according to equation (7). We employ the 20% tax share and obtain a range of tax elasticities of light oil between -0.1 (based on column 2) and -0.23 (based on column 1), both significant at the 0.01 level. It is encouraging to see that our previous estimate of the tax elasticity of -0.18 from Section 5.3.2 lies within this range.

We turn next to the natural gas results. As before, for the elasticity calculation we employ the share of tax in the net price of natural gas in 2015, which is 15%. This results in a range of tax elasticities of natural gas between -0.08 (based on column 4) significant at the 0.1 level and a non-significant -0.13 (based on column 3). According to column (8) of Table 8, the response of the demand for natural gas to the price increasing tax is entirely driven by plants in the service sector (elasticity of -0.17, significant at the 0.01 level), while the tax turns out to be insignificant in the industry service (see column 7). This finding also resonates with a previous result shown in Section 5.3.2 and Table 6, namely that the reductions in natural gas consumption in the post-policy period have been mainly carried out by plants in the service sector. Overall, this section confirms the previous estimations with an alternative empirical methodology used to estimate tax elasticities.

— Insert Figure 5 and Table 8 about here —

8 Conclusion

Ever since researchers have provided evidence for a causal link between man-made emissions of green house gases and global warming, there is a consensus that urgent actions are required to drastically reduce emission levels and avoid the dramatic consequences of global warming. However, no consensus has been reached regarding the key question on how to efficiently reduce the climate-damaging emissions. In fact, a broad spectrum of climate policy instruments are concurrently in use ranging from emission trading schemes, subsidies for renewable energy sources, emission target agreements to taxes on gasoline as well as taxes on carbon dioxide emissions. The main goal of these policies is to provide incentives for consumers and firms alike to switch to cleaner energy sources and/or to reduce their emissions of GHG into the atmosphere. In light of this broad variety of potential policy interventions, empirical evidence on the impact of various policies on energy consumption and emissions of firms and households is rather scarce, in particular with respect to the effects of a carbon tax on firm or plant outcomes.

This paper fills this gap partly by examining the impact of a rising carbon tax on subsequent plant behavior. Using plant-level data for the years 2001-2015, we study the effect of the introduction of a carbon tax on energy consumption and carbon dioxide emissions of plants active in the service and industry sector in Switzerland. The Swiss settings offers the unique possibility to observe the reaction of plants when exposed to a carbon tax that was drastically increased by 400% between 2008 and 2015.

Our results provide evidence for a substantial reduction of plants' carbon emissions of 12-15%, whereas energy consumption decreased by a relatively smaller 4-6% for the average plant.

This is consistent with tax elasticities that range between -0.1 and -0.23 for light oil and -0.17 for natural gas, the latter being mainly driven by plants in the service sector. There is some heterogeneity in how emission reductions were realized across sectors. While we observe reductions in fuel consumption in both the industry and service sector (intensive margin), we also find that plants in the industry sector increasingly switched to natural gas as a less carbon-intensive alternative (extensive margin). Moreover, these emission reductions driven by intensive and extensive margin adjustments are primarily achieved by more heavily taxed plants that feature a relatively more carbon-intensive energy mix and by plants with higher than subsector-median emission levels in the pre-policy period. More fundamentally, the general decrease in fuel consumption is probably driven by factors such as investments in better building insulation or the more widespread use of geothermal heat pumps. Our data does, however, not provide enough information to dig deeper into the mechanisms through which plants achieve their emission reductions. This would therefore be a fruitful area for future research.

References

Aatola, P., Ollikainen, M., & Toppinen, A. (2013). Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. Energy Economics, 36, 380-395.

Andersson, J. (2015). Cars, carbon taxes and CO2 emissions. London: Grantham Research Institute on Climate Change and the Environment.

Arrow, K., Jorgenson, D., Krugman, P., Nordhaus, W., & Solow, R. (1997). The Economists' Statement on Climate Change. Retrieved July, 30, 2006.

Bachmann, S., Scherer, R., Salamin, P. A., Ferster, M., & Gulden, J. (2014). Energieverbrauch in der Industrie und im Dienstleistungssektor–Resultate 2013. Helbling, Polyquest, Bundesamt für Statistik (BFS) & Bundesamt für Energie (BFE), Bern, August.

Bruvoll, A., & Larsen, B. M. (2004). Greenhouse gas emissions in Norway: do carbon taxes work?. Energy policy, 32(4), 493-505.

Bertrand, M., Duflo, E., & Mullainathan, S. (2004). How much should we trust differences-in-differences estimates?. Quarterly Journal of Economics, 119(1), 249-275.

Betz, R., & Sato, M. (2006). Emissions trading: lessons learnt from the 1st phase of the EU ETS and prospects for the 2nd phase.

Elkins, P., & Baker, T. (2001). Carbon taxes and carbon emissions trading. Journal of economic surveys, 15(3), 325-376.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. Journal of environmental economics and management, 55(2), 142-162.

Imbens, G. W., & Wooldridge, J. M. (2009). Recent developments in the econometrics of program evaluation. Journal of economic literature, 47(1), 5-86.

IEA (2017). CO_2 emissions from fuel combustion, Paris: International Energy Agency.

IEA (2018). Global Energy & CO_2 Status Report, March 2018, Paris: International Energy Agency.

IPCC (2013). Climate change 2013. The physical basis science. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., & Stern, N. (2018). Making carbon pricing work for citizens. Nature Climate Change, 8, 669-677.

Koch, N., Fuss, S., Grosjean, G., & Edenhofer, O. (2014). Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence. Energy Policy, 73, 676-685.

Li, S., Linn, J., & Muehlegger, E. (2014). Gasoline taxes and consumer behavior. American Economic Journal: Economic Policy, 6(4), 302-42.

Marion, J., & Muehlegger, E. (2008). Measuring illegal activity and the effects of regulatory innovation: Tax evasion and the dyeing of untaxed diesel. Journal of Political Economy, 116(4), 633-666.

Marion, J., & Muehlegger, E. (2011). Fuel tax incidence and supply conditions. Journal of Public Economics, 95(9-10), 1202-1212.

Martin, R., De Preux, L. B., & Wagner, U. J. (2014). The impact of a carbon tax on manufacturing: Evidence from microdata. Journal of Public Economics, 117, 1-14.

Metcalf, G. E. (2009). Market-based policy options to control US greenhouse gas emissions. Journal of Economic perspectives, 23(2), 5-27.

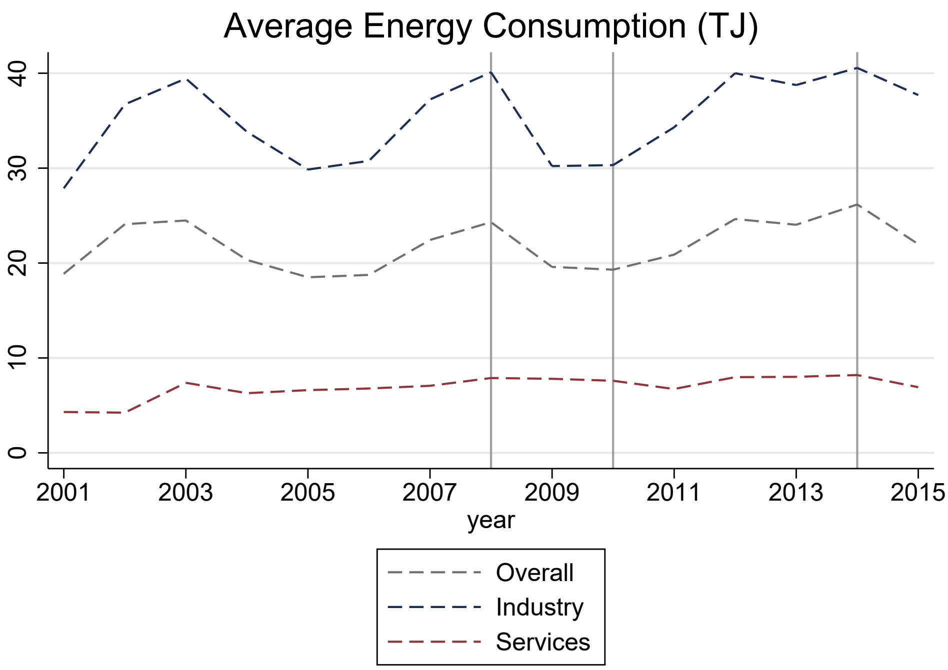
Stern, N., & Stiglitz, J. E. (2017). Report of the high-level commission on carbon prices. Washington D.C.: World Bank.

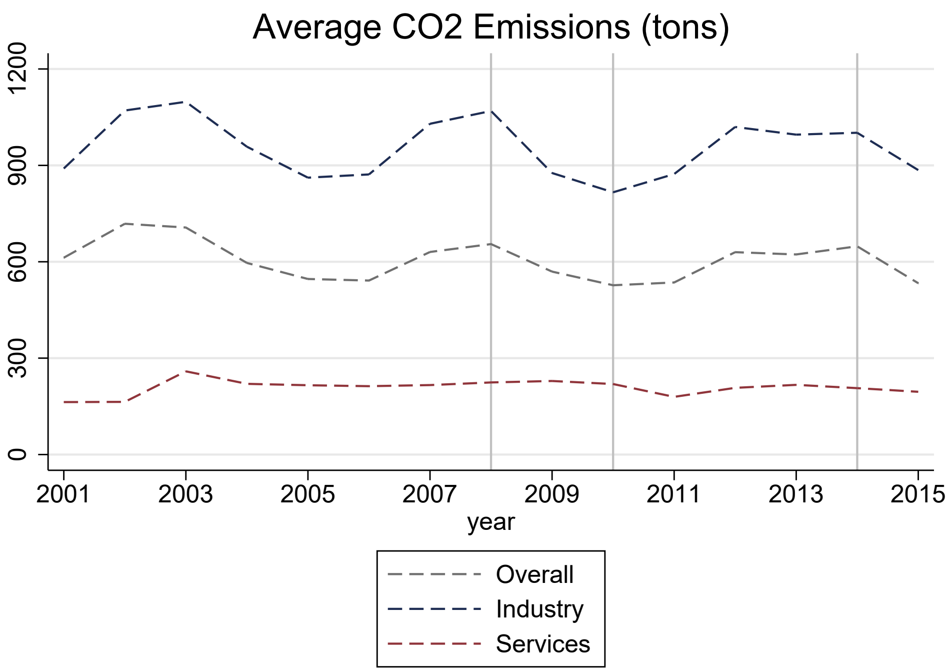
Verhoogen, E. A. (2008). Trade, quality upgrading, and wage inequality in the Mexican manufacturing sector. The Quarterly Journal of Economics, 123(2), 489-530.

Wooldridge, J. M. (2010). Econometric analysis of cross section and panel data. MIT press.

Tables and Figures

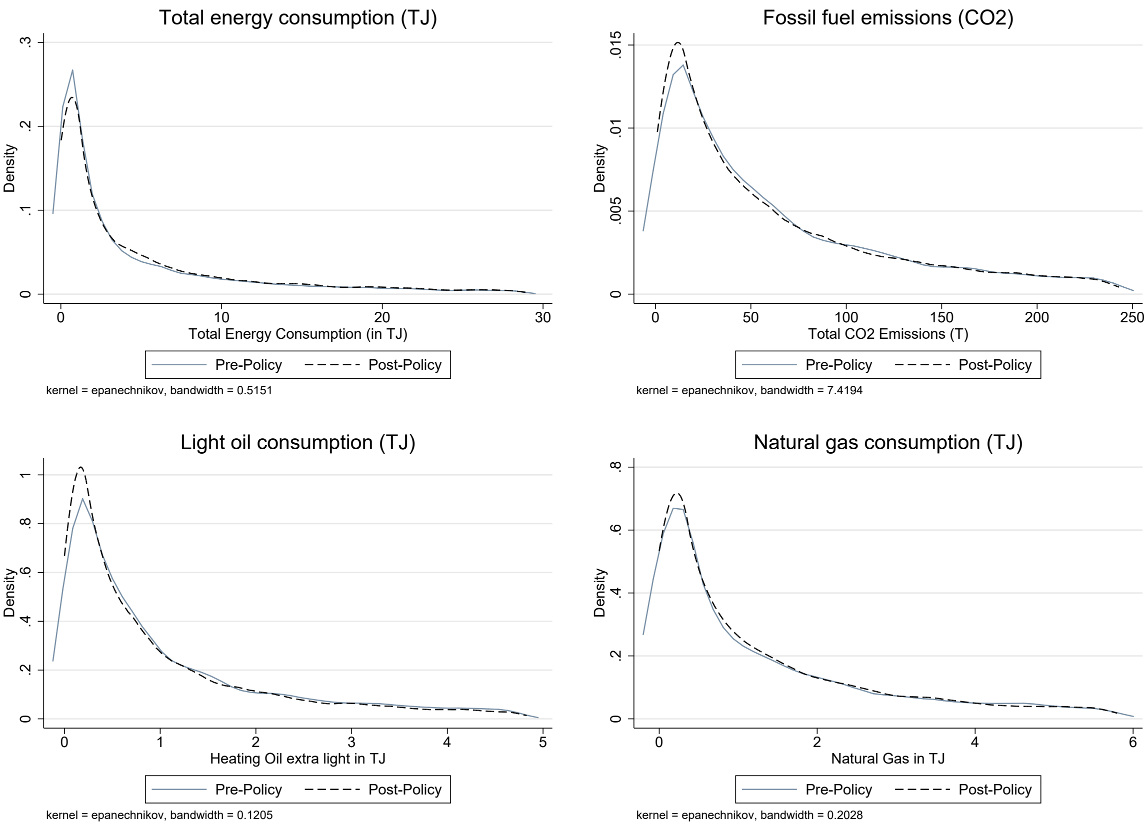
Figure 1: Total energy consumption and CO_2 emissions over time





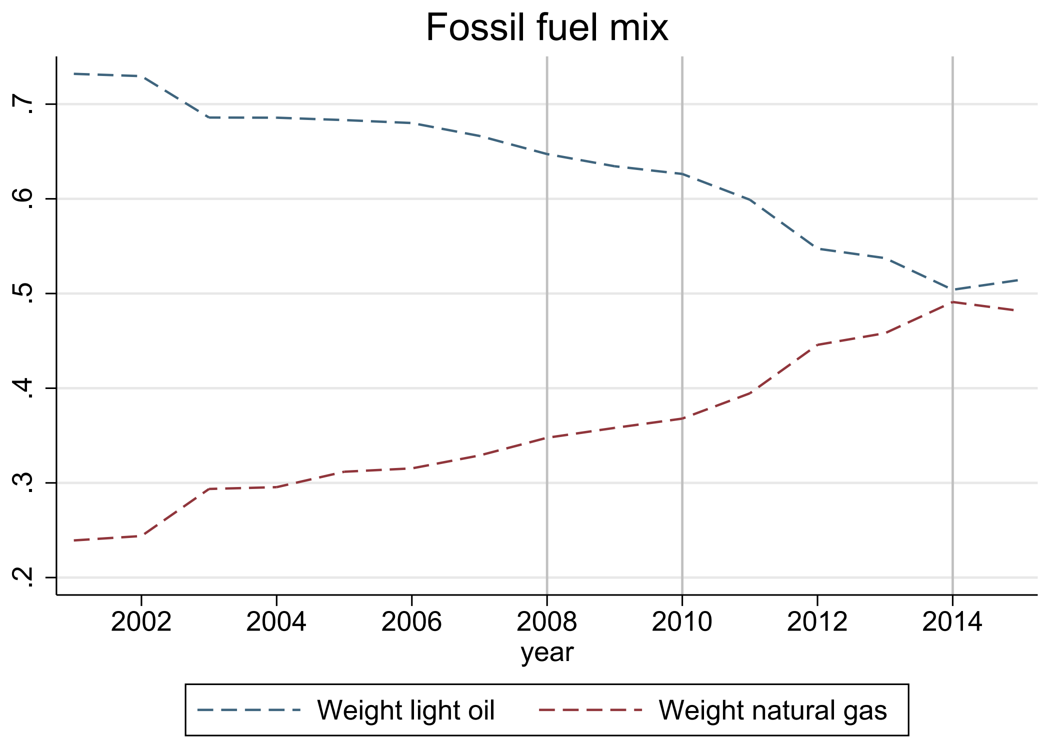
Notes: The figure illustrates the evolution of energy consumption (in TJ) and carbon dioxide emissions (in tons) by sector affiliation for the years 2001-2015.

Figure 2: Distribution plots:
Pre- and post policy change



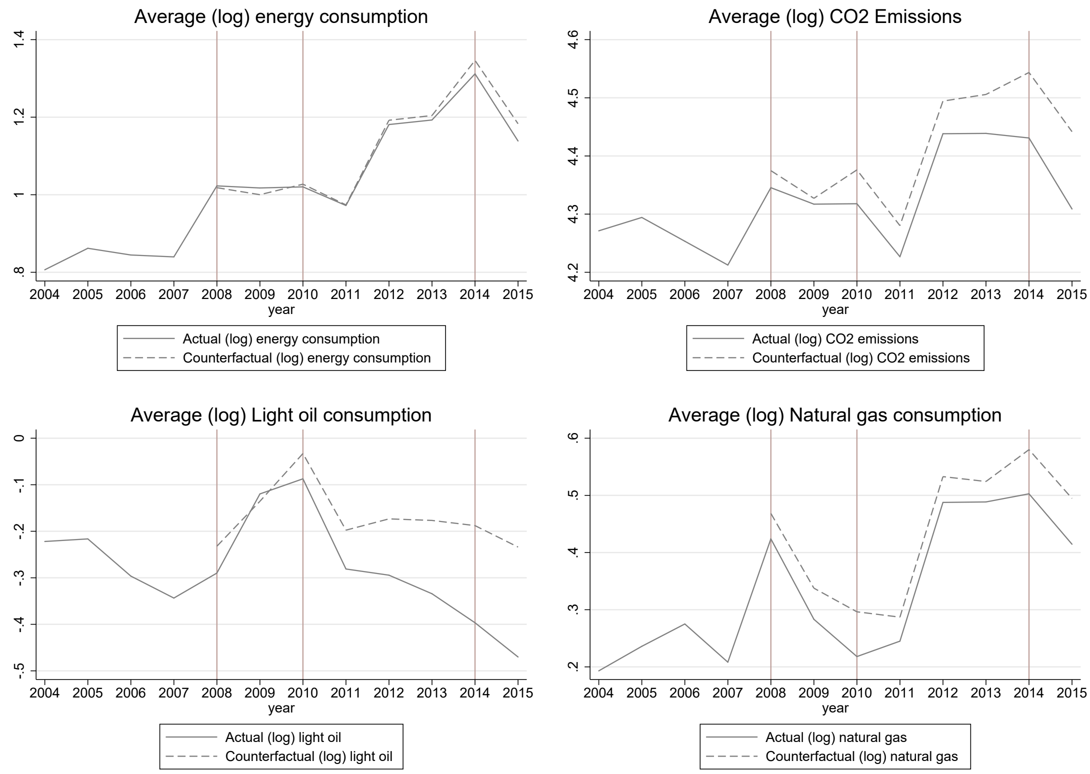
Notes: The graphs show the density of total energy consumption, fossil fuel emissions, light oil and natural gas consumption pre (solid line)- and post (dashed line) policy change for the years 2001-2015.

Figure 3: Development of fossil fuel mix



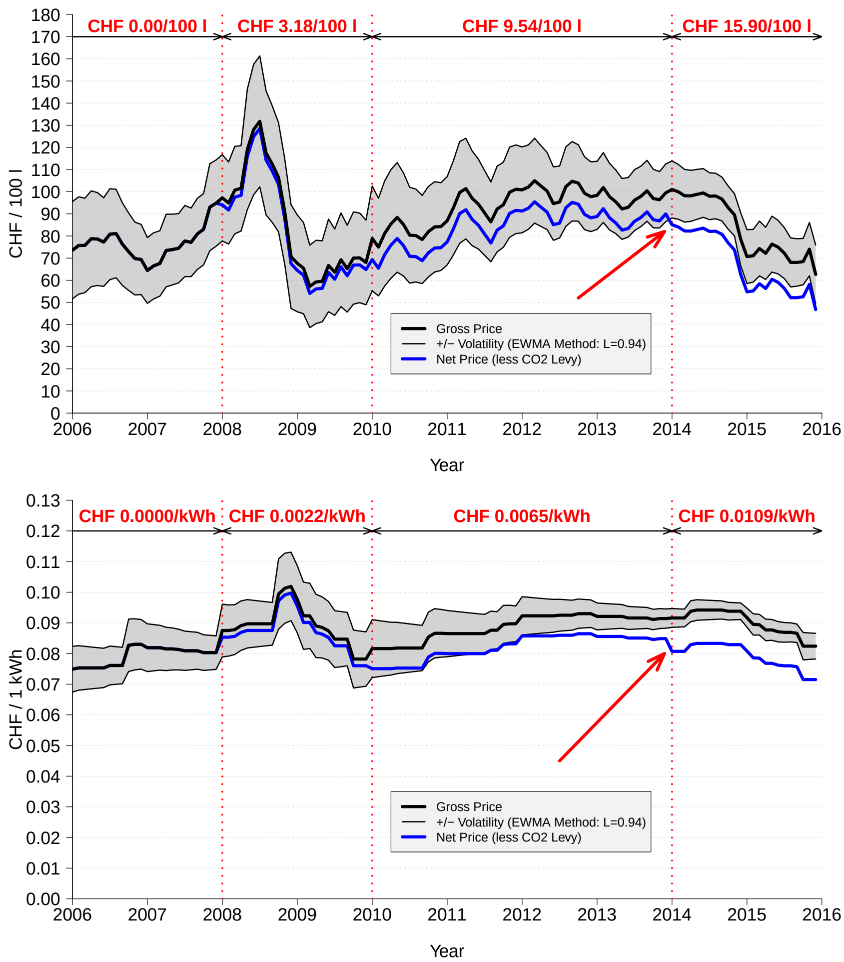
Notes: The graphs show the average share of light oil and natural gas in the plants fossil fuel mix over time.

Figure 4: Counterfactual plots



Notes: The graph shows the counterfactual and actual path of average (log) total energy consumption, carbon emissions, light oil and natural gas consumption before and after the introduction of the carbon tax. Counterfactuals are constructed based on the above described FE specification (1) in Section 4.

Figure 5: Price charts of Light oil (upper panel) and natural gas (lower panel)



Notes: The figure shows the gross prices (black) and net prices (net of CO_2 tax) prices (blue) of (heating) light oil (upper panel) and natural gas (lower panel).

Table 1: Tax burden by type of fossil fuel

Years	**Tax**	**Light oil**	**Natural gas**
	CHF/t CO_2	CHF/TJ	CHF/TJ
2008-09	12	885	673
2010-2013	36	2654	2020
2014-2016	60	4423	3366

Source: Federal Office for the Environment (2018). *Notes:* The base value of the CO2 levy is in CHF per ton of CO2 equivalents. The tax is converted into CHF per TJ. In accordance with the predefined emission reduction path for thermal fuels, The CO2 levy was increased three times between the introduction in 2008 and 2016.

Table 2: Summary statistics

	Pre-policy			*Post-policy*		
	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs
Plant outcomes						
Total Energy Consumption (in TJ)	20.88	150.05	21303	22.52	143.75	23606
Total CO_2 emissions (in tons)	611.94	4038.56	21303	589.46	3497.70	23606
Light oil (in TJ)	2.46	7.99	21303	1.73	5.47	23606
Share light oil (% fossil fuel mix)	0.70	0.44	21086	0.58	0.48	23521
Natural gas (in TJ)	6.29	58.75	21303	7.67	58.03	23606
Share natural gas (% fossil fuel mix)	0.30	0.44	21086	0.42	0.48	23521
Electricity consumption (in TJ)	8.86	69.38	21303	9.58	60.30	23606
Share electricity (% total energy cons.)	0.41	0.24	21303	0.46	0.24	23606
Sector affiliation						
Service sector	0.47	0.50	21303	0.48	0.50	23606
Food production	0.04	0.19	21303	0.04	0.20	23606
Textile/Leather	0.04	0.19	21303	0.03	0.16	23606
Paper/Printing	0.05	0.21	21303	0.04	0.20	23606
Chemicals/Pharmaceuticals	0.04	0.20	21303	0.03	0.18	23606
Other Non-metallic Minerals	0.03	0.17	21303	0.02	0.14	23606
Iron/Steel	0.02	0.14	21303	0.02	0.13	23606
Other Non-ferrous Metals	0.01	0.08	21303	0.01	0.11	23606
Metal Products/Equipment	0.11	0.31	21303	0.14	0.34	23606
Machinery	0.05	0.22	21303	0.06	0.24	23606
Other Industries	0.11	0.31	21303	0.08	0.27	23606
Construction	0.04	0.21	21303	0.05	0.22	23606
Trade	0.13	0.34	21303	0.12	0.32	23606
Accommodation/Food Service	0.04	0.20	21303	0.05	0.22	23606
Financial and Insurance Services	0.04	0.19	21303	0.04	0.18	23606
Public Administration	0.02	0.16	21303	0.03	0.16	23606
Education	0.07	0.25	21303	0.07	0.25	23606
Health/Social Work	0.07	0.26	21303	0.08	0.28	23606
Other Services	0.09	0.29	21303	0.10	0.30	23606
Plant characteristics						
Full-time employees	96.46	185.16	21303	122.83	252.15	23606
Part-time employees	21.57	79.18	21303	32.98	108.69	21454
Gross Floor Area (m^2)	9089.84	24081.56	21303	10784.02	24916.98	23606

Notes: Summary statistics for the pre- and post-policy years.

Table 3: Carbon tax effect estimates

Carbon policy effects														
Outcome Variable	**ln(Total cons)**		**ln(CO_2 Emissions)**		**ln(Light oil)**				**ln(Natural gas)**				**ln(Electricity)**	
					Extensive Margin		Intensive Margin		Extensive Margin		Intensive Margin			
Specification	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
$D_{2008-09}$ (12 CHF/t CO_2)	0.01	0.01*	-0.01	-0.02**	-0.01**	0.01	-0.01	-0.03*	0.01**	0.00	-0.03	-0.04	0.01	0.03***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.02)	(0.00)	(0.00)	(0.02)	(0.02)	(0.01)	(0.01)
$D_{2010-13}$ (36 CHF/t CO_2)	-0.00	-0.01	-0.03**	-0.06***	-0.03***	-0.02***	-0.07***	-0.10***	0.01**	0.01**	-0.02	-0.05	-0.00	0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.00)	(0.03)	(0.03)	(0.01)	(0.01)
$D_{2014-15}$ (60 CHF/t CO_2)	-0.06***	-0.04***	-0.15***	-0.12***	-0.05***	-0.03***	-0.24***	-0.21***	0.02***	0.02***	-0.14***	-0.10**	-0.04**	-0.03**
	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.03)	(0.01)	(0.01)	(0.04)	(0.04)	(0.01)	(0.01)
Plant fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plant characteristics	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Economic activity indicators	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Number of Observations	44909	44909	44909	44909	44909	44909	32628	32628	44909	44909	18406	18406	44909	44909

Notes: The table shows the estimated carbon tax effects on (logarithmized) total energy consumption, CO_2 emissions, light oil, natural gas and electricity consumption (all in TJ) using the above outlined FE specifications. Moreover, the table shows the estimated policy effects at the both the extensive (i.e. the yes/no decision of use) and intensive margin (i.e. the quantity response if using) for light oil and natural gas consumption. Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.

Table 4: Long differences ln CO2 Emissions 2008-2015 compared to 2001-2008

Outcome Variable				**Δln(CO2 Emissions)**				
Period		2008-2015 (1)-(3)		2001-2008		2008-2015 (5)-(7)		2001-2008
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
High tax (Pure light oil user, 2008)	-0.31***		-0.31***					
	(0.05)		(0.05)					
High tax (Pure light oil user, 2001)		-0.29***		-0.08**				
		(0.05)		(0.04)				
Tax intensity (Share light oil, 2008)					-0.29***		-0.29***	
					(0.05)		(0.05)	
Tax intensity (Share light oil, 2001)						-0.26***		-0.08*
						(0.04)		(0.04)
Difference (15-08 vs. 08-01)		-0.23*** (1) minus (4)				-0.21*** (5) minus (8)		
p-value (H0: no difference)			<0.001				<0.001	
Observations	367	367	367	367	507	507	507	507
Estimation	OLS	OLS	IV	OLS	OLS	OLS	IV	OLS
Instrument			High tax 2001				Tax int. 2001	
Cragg-Donald F statistics (Weak identification test):			4639.300				3660	
Stock-Yogo critical value (10% maximum IV bias):			16.38				16.38	

Notes: All specifications include plant fixed (differenced away), trends at the subsector level and the change in log number of employees and floor size as covariates. p-values on differences allow for error correlation between equations. Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.

Table 5: Tax intensity estimates

Tax intensity effects								
Outcome Variable			**ln(CO_2 Emissions)**				**ln(Electricity)**	
Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
High tax$_{2008-09}$	-0.03	-0.04*	-0.05	-0.04*			0.01	
	(0.03)	(0.02)	(-0.04)	(0.02)			(0.01)	
High tax$_{2010-13}$	-0.11***	-0.07*	-0.13***	-0.07*			0.04*	
	(0.04)	(0.04)	(-0.04)	(0.04)			(0.02)	
High tax$_{2014-15}$	-0.13**	-0.07	-0.14***	-0.07			0.05*	
	(0.05)	(0.05)	(-0.05)	(0.05)			(0.02)	
High tax$_{2006-07}$			-0.04*	-0.01				
			(0.02)	(0.01)				
High tax$_{2004-05}$			-0.04*	-0.01				
			(0.02)	(0.01)				
ln(Plant tax)					-0.34***	-0.18***		0.02*
					(0.11)	(0.04)		(0.01)
Plant characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plant fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	No	Yes	No	Yes	No	Yes	Yes	Yes
Sector-year fixed effects	Yes	No	Yes	No	Yes	No	No	No
Plant-specific time trends	No	Yes	No	Yes	No	Yes	Yes	Yes
Number of Observations	28809	28809	28809	28809	28809	28809	28809	13548

Notes: Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.

Table 6: Carbon taxes and plant outcomes by sector

Carbon policy effects by sector affiliation														
Outcome Variable	**ln(Total cons)**		**ln(CO_2 Emissions)**		**Light oil (Y/N)**		**ln(Light oil)**		**Natural gas (Y/N)**		**ln(Natural gas)**		**ln(Electricity)**	
	Industry	Services	Industry	Services	Industry	Services	Industry	Services	Industry	Services	Industry	Services	Industry	Services
$D_{2008-09}$ (12 CHF/t CO_2)	0.01	0.00	-0.02	-0.02	-0.00	-0.00	-0.06**	0.01	0.01	-0.01	-0.03	-0.06	0.03***	0.02*
	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.03)	(0.01)	(0.01)	(0.04)	(0.04)	(0.01)	(0.01)
$D_{2010-13}$ (36 CHF/t CO_2)	-0.00	-0.02	-0.06***	-0.06***	-0.02***	-0.01	-0.15***	-0.05	0.01**	0.00	-0.01	-0.08**	0.02*	-0.01
	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.03)	(0.01)	(0.01)	(0.04)	(0.04)	(0.01)	(0.01)
$D_{2014-15}$ (60 CHF/t CO_2)	-0.04**	-0.05***	-0.13***	-0.13***	-0.04***	0.01	-0.26***	-0.19***	0.03***	0.01	-0.01	-0.17***	-0.02	-0.04*
	(0.02)	(0.02)	(0.03)	(0.03)	(0.01)	(0.01)	(0.05)	(0.06)	(0.01)	(0.01)	(0.06)	(0.06)	(0.02)	(0.02)
Plant fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plant characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic activity indicators	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations	23533	21376	23533	21376	23533	21376	18296	14332	23533	21376	8563	9843	23533	21376

Notes: Fixed effects estimates of the carbon tax on plant outcomes by sector affiliation. Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.

Table 7: Above and below sector-median emissions and plant outcomes

Outcome Variable	**Δln(CO2 Emissions)**		**ln(CO2 Emissions)**		**ln(Light oil)**		**ln(Natural gas)**		**ln(Total cons)**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample wrt median emissions	full sample		above	below	above	below	above	below	above	below
High emission (in 2008)	-0.26***									
	(0.04)									
High emission (in 2001)		-0.12***								
		(0.04)								
D_{08-09}(12 CHF / t CO_2)			-0.03**	-0.02	-0.05**	-0.00	-0.03	-0.02	-0.00	0.03**
			(0.01)	(0.02)	(0.03)	(0.02)	(0.03)	(0.05)	(0.01)	(0.01)
D_{10-13} (36 CHF / t CO_2)			-0.10***	0.01	-0.12***	0.00	-0.08**	0.07	-0.03***	0.04**
			(0.02)	(0.03)	(0.03)	(0.03)	(0.04)	(0.06)	(0.01)	(0.02)
D_{14-15} (60 CHF / t CO_2)			-0.16***	-0.04	-0.22***	-0.12**	-0.17***	0.16*	-0.07***	0.02
			(0.02)	(0.04)	(0.05)	(0.05)	(0.05)	(0.10)	(0.01)	(0.02)
Diff. (08-15 vs. 01-08)	-0.14**									
p-value (H0: no difference)	p¡0.05									
Period	2008-2015	2001-2008	2001-2015 (3)-(15)							
Data interval	Long differences (1)-(2)		Annual data points (3)-(15)							
Number of Observations	507	507	21,567	9,909	16,410	7,099	10,132	3,147	21,976	16,154

Notes: All specifications include plant characteristics (change in log number of employees and floor size in columns 1 and 2 and in levels in columns 3 to 10) and plant fixed effects. Columns 1 and 2 include subsector trends, while columns 3 to 10 employ a linear time trend. Columns 3 to 10 also include economic activity and weather indicators. Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.

Table 8: Tax elasticity estimates

Outcome Variable	**ln(Light Oil)**		**ln(Natural gas)**		**ln(Light oil)**		**ln(Natural gas)**	
Sectors	Industry & Services (1)-(4)				Industry	Services	Industry	Services
Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(net light oil price, pre-tax)	-0.20***	-0.01			0.03	-0.07**		
	(0.03)	(0.02)			(0.02)	(0.03)		
ln(1+ tax / net light oil price)	-1.16***	-0.52***			-0.51***	-0.62***		
	(0.24)	(0.13)			(0.17)	(0.21)		
ln(net natural gas price, pre-tax)			-0.11	-0.04			0.02	-0.13
			(0.19)	(0.12)			(0.15)	(0.18)
ln(1+ tax / net natural gas price)			-0.92	-0.52*			0.09	-1.14***
			(0.66)	(0.32)			(0.45)	(0.44)
Time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic activity / weather indicators	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Plant characteristics	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Plant fixed effects	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Number of Observations	43,708	43,708	25,013	25,013	23,224	20,484	10,734	14,279

Notes: Standard errors clustered at the plant level in parentheses: *** $p < 0.01$ ** $p < 0.05$ * $p < 0.1$.