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Abstract

Prompted by the ongoing political and academic debate regarding decarbonization, we empirically studied how firms responded to the introduction of a gradually increasing carbon tax. The Swiss context offers a unique opportunity to observe reactions to a carbon tax that increased by 400 percent between 2008 and 2015. Using firm-level panel data, we found that this tax led to small but statistically significant reductions in energy consumption. The effect on CO_2 emissions was greater, with up to eight percent. These reductions can be attributed to businesses in the industrial sector replacing light oil with natural gas and reducing overall oil consumption. Businesses in the service sector consumed less of both fossil fuels. We also found that companies showed a negligible response to changes in the net price of energy sources but, instead, reacted to the carbon tax. We estimated a tax elasticity of - 0.17 for the consumption of light oil and - 0.10 for natural gas.

JEL Classification: Q58, C23, C21

Keywords: carbon tax, firm behavior, emissions, energy consumption, tax elasticity

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1 INTRODUCTION

Global warming is one of the most fundamental and pressing challenges humankind is currently facing. The rise in the global average temperature is predicted to intensify the occurrence of natural disasters and will lead to a substantial rise of 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 in the atmosphere over time and are the main culprit in anthropogenic global warming (IPCC, 2013)[1]. Although the use of fossil fuels has been decreasing since the 1960s, they still account for 80 percent of today's global energy consumption (World Bank, 2020b). To counter the adverse long-term consequences of global warming, the UN Framework Convention on Climate Change was adopted in 1992. It aims to "stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Art. 2, UNFCCC). In the more recent UN Paris conference in 2015, nearly 200 countries agreed to limit the increase in the global average temperature to well below 2º Celsius above pre-industrial levels.

It is a broad consensus among economists that putting a price on carbon emissions, either through the introduction of taxes or via emission trading schemes, is a cost-efficient approach to reducing CO_2 emissions and internalizing the external costs of pollution (Baranzini & Carattini 2014; Elkins & Baker 2001; Arrow et al. 1997). Nonetheless, 85 percent of current global greenhouse emissions are not priced, including emissions from large emitting countries such as the United States, India, and Russia (Stern & Stiglitz, 2017). This lack of more widespread implementation of carbon pricing schemes may be explained by their low current political acceptability among the general public, in particular, due to concerns about their distributional effects (Klenert et al., 2018; Jiang & Shao, 2014; Shammin & Bullard, 2009; Kerkhof et al., 2008). Despite the importance of this topic, the empirical evidence on the *ex-post* effects of carbon taxes on household and firm behavior remains scarce (Andersson 2019; Aghion et al. 2016; Li et al. 2014; Murray & Rivers 2015; Rivers & Schaufele 2015; Sterner 2015; Martin et al. 2014a; Davis & Kilian 2011; Bjørner & Jensen 2002)[2]. Additional research

[1] Global CO_2 emissions reached a historic high of 32.8 gigatons (Gt) in 2017 (IEA, 2019a).

[2] In contrast, the interplay between emission trading systems and firm behavior has received considerably more attention in previous work (e.g., Koch et al. 2014; Aatola et al. 2013; Betz & Sato 2006).

on the effectiveness of carbon pricing may thus enhance its credibility and acceptability and its subsequent implementation across a larger number of political entities.

In this paper, we study the impact of the introduction and gradual increase of a carbon tax on the behavior of firms active in the service and industry sectors in Switzerland. Using firm-level panel data for the years 2002-2015, we provide micro-econometric evidence on how firms' energy consumption and CO_2 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 (Metcalf 2009; Fischer & Newell 2008 for an overview). Our findings are highly relevant for policymakers as the industry and service sectors account for about 40 percent of global emissions (IEA, 2019a).

In terms of its empirical scope and the data used, our study is most closely related to the research of Martin et al. (2014a) in the United Kingdom, who found significant reductions in the energy intensity and electricity use of manufacturing plants in response to the introduction of the UK carbon tax in the early 2000s. A notable difference to their study is that the Swiss setup is a unique opportunity to observe how firms respond to an increasing carbon tax. In fact, in Switzerland, the tax was introduced in 2008 and gradually increased by 400 percent in the subsequent years.

Moreover, and in contrast to the existing empirical evidence, we present novel insights about substitution patterns across energy sources as our data allows us to capture the carbon tax effect on firms' consumption of light oil, natural gas, and electricity at the extensive and the intensive margin. Besides, we contribute to a deeper understanding of the heterogeneous effects of the carbon tax across firms from different sectors.

Our results show that the carbon tax has led to a significant reduction in total energy consumption by about 4% for a typical firm in the sample, and the energy savings can be attributed to the last post-policy period (2012-2015) when the tax was raised to its maximum during the observation window. Moreover, our estimates indicate systematic reductions in carbon emissions as a response to the tax. However, we also found evidence that the initial tax level was too low to produce a significant response from firms. With the subsequent increase in the tax, significant reductions between three percent in the second post-policy period (2010-2012) and up to eight percent in the third post-policy period (2013-2015) were realized. Given that the average pre-policy emission level was at approximately 325 tonnes of CO_2, the estimated policy effects are sizeable and imply reductions in the magnitude of about 25 tonnes of CO_2. In accordance with these findings, we show that the tax significantly decreased the average carbon intensity of firms. Moreover, we show that the described emission reductions were achieved by reductions in the consumption of light oil and the substitution of light oil with the less CO_2-intensive natural gas.

This observation masks some substantial differences, however, as to "how" the emission reductions were achieved across industries: While the industry sector reduced light oil consumption and started the substitution of light oil with natural gas, firms in the service sector uniformly reduced fuel consumption across both fuel types, for the most part without switching to the less carbon-intensive natural gas.

In the second step of the analysis, we confirm the importance of the carbon tax effect by providing estimates of the tax elasticity for the consumption of fossil fuels. We found that firms in both sectors show a negligible response to changes to the net prices of energy sources. However, we provide evidence of significant and sizeable tax elasticities that are consistent with previous results: While the tax elasticity for the consumption of light oil ranges from -0.06 to -0.17, the effect of the tax on natural gas is entirely driven by the service sector, with an estimated elasticity of -0.10 (Marion & Muehlegger 2008; Li et al. 2014).

The remainder of the paper is organized as follows: In Section 2, we describe the institutional background and give 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 firm outcomes and present the corresponding main findings. In a final analysis, we provide tax elasticity estimates (5), and we draw conclusions in Section 66

2 Institutional Background

2.1 The Swiss Carbon Tax

Under the Kyoto Protocol, Switzerland agreed to reduce its greenhouse gas (GHG) emissions by eight percent relative to the levels of 1990 in the period 2008 - 2012. In addition, the GHG reduction target was increased to 20 percent in the second Kyoto commitment period of 2013-2020 (Federal Office for the Environment [FOEN], 2018). To reach these ambitious emission reduction goals, the Federal Act on the Reduction of CO_2 Emissions was enacted by the Swiss parliament in 2008, thus introducing three main climate policy instruments: the Swiss emission trading scheme (ETS), target agreements, and - most relevant for the majority of firms in the industry and service sectors - a CO_2 levy on fossil fuels. Figure 1 shows the share of firms covered by each of the three instruments in each sector in 2015. Depending on some requirements, such as the level of emissions, firms are either regulated by the ETS, or they may opt for a target agreement. In both cases, a refund of the CO_2 levy is possible.[3] As Figure 1 illustrates, the carbon tax is by far the most common policy instrument, covering more than 95 percent of companies active in Switzerland. This, therefore, defined our study population.

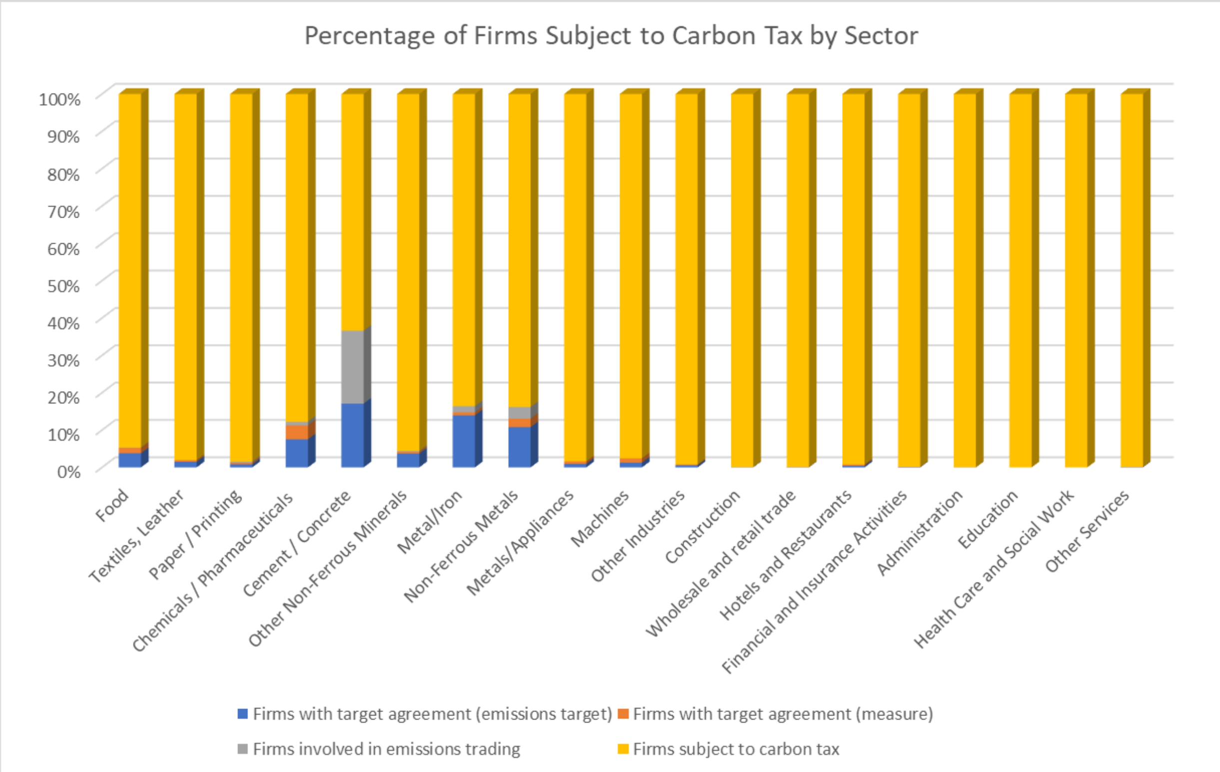

Figure 1 *% Percentage of firms in each sector covered by one of the major climate policy instruments in 2015 in Switzerland*

Notes: Based on data from the annual survey of the energy consumption in the industry and service sectors carried out by the Swiss Federal Office of Energy. To estimate the number of firms subject to carbon tax, the number of firms regulated by an emissions or measure target agreement (https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/klimapolitik/co2-abgabe/befreiung-von-der-co2-abgabe-fuer-unternehmen.html) or by emissions trading (https://www.emissionsregistry.admin.ch/) was subtracted from the total number of firms in a sector and is shown separately.

The CO_2 levy is a per-unit tax on CO_2 emissions from the consumption of fossil fuels including heating oil, natural gas, and coal.[4] However, the Swiss carbon tax is not a pure price instrument but rather a hybrid instrument. It resembles the so-called standard-price approach, which was advocated by Baumol and Oates (1971) as a practical solution to overcome the difficulties in estimating the marginal net damages a Pigouvian tax would require. They suggested setting a

[3] Firms are required to participate in the ETS if i) they are listed in the Annex 6 to the Swiss CO_2 Ordinance and ii) if their total emissions in each of the previous three years are equal or above 25,000 tonnes of CO_2 equivalents.

[4] Motor fuels are not subject to the CO_2 levy but are subject to a separate petroleum tax.

political, quantitative target and - since price elasticities of demand are unknown - starting with a tax rate and adjusting it iteratively if the target is not met. This is also the approach taken concerning Swiss carbon levy regulation. The directive[5] specifies that if emissions in a specific year exceed a certain level, the tax rate will automatically be increased. If, for example, the CO_2 emissions of the regulated sectors were above 79 percent of 1990 emissions on 1 January 2012, the tax rate would have been increased from CHF 36 to CHF 60 per ton of CO_2 from 1 January 2014. In other words, a quantity target is set and, based on trial and error, the tax rate is adjusted to meet the target. This approach provides firms with a high level of certainty for their mitigation investments as the tax rate either remains the same or is increased by a pre-defined amount, which confirms that carbon tax can, in fact, provide a level of certainty with respect to emission quantities as well as price, a question recently discussed in a symposium on the design of a U.S. carbon tax (Aldy, 2014).

The initial level of the carbon tax was set at CHF 12 per tonne of CO_2 emissions in 2008. In 2010, the tax was raised to CHF 36, in 2014 to CHF 60, in 2016 to CHF 84, and in 2018, it was increased again to CHF 96. Public revenues from the CO_2 levy amounted to CHF 1.1 billion in 2016. 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 a program for the renovation of buildings to improve their energy efficiency (building program).

[5] Art. 94 of the Swiss CO_2 Act

2.2 TAX BURDEN UNDER THE SWISS CARBON TAX

Since the Swiss carbon tax is based on the amount of CO_2 emissions in tonnes, it varies substantially across different fossil fuel types depending on their carbon intensity. To illustrate, below shows the tax burden by type of fossil fuel and terajoule (TJ) of energy consumption over time. It also shows that firms who rely on energy from light oil face substantially higher taxes per TJ of energy consumed than those using energy mainly 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 tonne of CO_2 emissions (*i*) rapidly increased over time, and (*ii*) a growing wedge in the tax burden between light oil and natural gas developed, rendering light oil consumption increasingly less attractive compared to natural gas. In numbers, while firms paid CHF 885 per TJ of energy from light oil in 2008-2009, the same amount of energy from natural gas resulted in CHF 673 in carbon taxes. Between 2010 and 2013, the tax burden per TJ increased to CHF 2,654 for light oil and CHF 2,020 for natural gas. Finally, in the third post-policy period (2014-2016), when the carbon tax was increased to CHF 60 per ton of CO_2 emissions, the tax burden per TJ increased to CHF 4,423 for light oil and CHF 3,366 for natural gas, resulting in a tax differential of more than CHF 1,000 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. This will affect firms' current and future investment decisions, which will, in turn, be reflected by their levels of CO_2 emissions.

Table 1: Tax Burden by Type of Fossil Fuel

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

Notes: The base value of the CO_2 levy is in CHF per tonne of CO_2 equivalents. The tax is converted into CHF per TJ. In accordance with the predefined emission reduction path for thermal fuels, The CO_2 levy was increased three times between the introduction in 2008 and 2016. *Source:* Federal Office for the Environment (2018).

The tax is collected by the Federal Customs Authority and applied to producers or importers of fossil fuels, who have to separately show the tax on any bill. This ensures that the tax is passed on to the end-consumers without distortions, but it also means that companies that are part of the ETS or have a target agreement must pay the tax directly and will only be reimbursed on request. The carbon tax, therefore, has implications for the financial liquidity of firms. For ETS firms, allowances are generally allocated free of charge, which reduces the financial burden. Firms that voluntarily opt for a target agreement will have to meet either an emission target or implement economically viable measures (see Figure 1). Such measures are calculated on a pay-back period of four or nine years and take the CO_2 levy into account.

3 DATA

The evaluation is based on data from the annual survey of the energy consumption in the industry and service sectors carried out by the Swiss Federal Office of Energy (see Bachmann et al., 2014 or Sauvin et al., 2017). According to the Federal Business and Enterprise Register (Swiss Federal Statistical Office [SFSO], 2018), a representative sample of 12,000 firms[6] has to report their final energy consumption every year. The Swiss Federal Office of Energy (SFOE) has defined 19 sectors, based on the two-digit general classification of economic activities code (SFSO, 2008). For our main analysis, we used these firm-level data for the years 2001-2015. This data set offers detailed information on a firm's annual energy consumption by fuel, as well as a series of characteristics of firms, including the number of employees, sector affiliation, and floor space. We restricted our analysis to firms that use exclusively light oil, natural gas, or electricity as their primary energy source.[7] Firms with a single occurrence in the data as well as firms in sub-sectors with less than 90 percent of firms subjected to the carbon tax were excluded.[8] Applying these sample restrictions left us with an unbalanced panel of 56,353 observations from 11,011 firms active in the industry (53 percent) and service sectors (47 percent) between 2002-2015.

[6] According to the definition of the SFOE, a firm is a separated unit of a company at which location one or more people are working. A unit means a building, a building complex, or a part of a building.

[7] Other energy sources such as heavy oil, natural wood and industrial waste are of low relevance as they account for less than three percent of the overall energy consumption of firms in the sample. Moreover, relaxing the corresponding restriction does not alter the main findings in any significant way.

[8] The cement, chemicals, metal/iron, and non-ferrous metal industries were excluded. Again, the inclusion of these firms would not affect our results significantly. The corresponding robustness checks are available upon request.

3.1 DESCRIPTIVE EVIDENCE

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 years in Table 2. The table gives detailed information about the consumption of different energy sources including light oil, natural gas, and electricity. For our study, we converted fossil fuel energy sources into their CO_2 equivalents in tons and computed the CO_2 intensity[9] as well as indicators for the share of light oil and natural gas in each firm's energy mix.

The pre-post mean comparison of the described outcomes shows that the average firm energy consumption has slightly increased over time from roughly 9.1 to 9.5 TJ. Yet, the difference in means is not statistically significant, which suggests that the average firm did not adjust the level of energy consumption systematically in the observation window. However, the raw mean comparison shows a decrease of approximately 25 tonnes of CO_2 emissions for the average firm 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 tax as there are many possible channels which could plausibly explain the observed drop in emissions. For example, the decrease in emissions can at least be partly explained by the significantly lower economic growth that followed the financial crisis of 2008-2009, which persisted during the entire post-policy period.[10] Besides such macroeconomic shocks or comparable changes in the institutional setting which affected all firms in the economy, technological advancements, or general changes in firm characteristics might have caused the emission levels to decrease. Finally, the pre-post mean comparison provides prime evidence for substitution patterns among the different energy sources as we observed 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 firms' fossil fuel mix.

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[9] The carbon intensity reflects the amount of CO_2 emitted per TJ of energy consumed (see Subsection 3.2 for details).

[10] 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.

Table 2 Summary Statistics

	Pre-policy			Post-policy		
	Mean	**Std.Dev.**	**Obs**	**Mean**	**Std.Dev.**	**Obs**
Firm-Level Outcomes						
Energy Consumption (in TJ)	9.14	32.41	22648	9.45	32.04	26742
CO_2 Emissions (in tonnes)	325.88	1475.28	22648	300.51	1334.84	26742
Carbon Intensity (per TJ)	40.18	17.24	22648	36.45	16.91	26742
Light Oil Consumption (in TJ)	2.08	6.72	22648	1.39	4.25	26742
Share Light Oil (% Energy Consumption)	0.41	0.33	22648	0.32	0.32	26742
Natural Gas Consumption (in TJ)	3.05	24.09	22648	3.51	22.79	26742
Share Natural Gas (% Energy Consumption)	0.18	0.29	22648	0.22	0.30	26742
Electricity Consumption (in TJ)	4.00	10.97	22648	4.55	12.57	26742
Share Electricity (% Energy Consumption)	0.41	0.24	22648	0.45	0.24	26742
Firm Characteristics						
Full-Time Employees	89.58	170.88	22648	101.04	195.03	26742
Part-Time Employees	21.13	79.51	22648	28.36	95.32	24242
Gross Floor Area (in m^2)	7590.00	18644.95	22648	8089.63	19317.50	26742
Sector Affiliation						
Share Service Sector	0.53	0.50	22648	0.53	0.50	26742
Food Production	0.04	0.19	22648	0.04	0.20	26742
Textile/Leather	0.04	0.19	22648	0.03	0.16	26742
Paper/Printing	0.05	0.21	22648	0.04	0.20	26742
Other Non-Metallic Minerals	0.03	0.16	22648	0.02	0.15	26742
Metal Products/Equipment	0.11	0.32	22648	0.14	0.35	26742
Machinery	0.05	0.23	22648	0.06	0.24	26742
Other Industries	0.10	0.30	22648	0.08	0.26	26742
Construction	0.05	0.22	22648	0.06	0.23	26742
Trade	0.15	0.35	22648	0.14	0.34	26742
Accommodation/Food Service	0.05	0.22	22648	0.05	0.23	26742
Financial and Insurance Services	0.04	0.20	22648	0.04	0.20	26742
Public Administration	0.03	0.17	22648	0.03	0.17	26742
Education	0.09	0.28	22648	0.07	0.26	26742
Health/Social Work	0.08	0.27	22648	0.08	0.27	26742
Other Services	0.10	0.30	22648	0.12	0.32	26742

Notes: Summary statistics for the pre- (2002-2007) and post-policy (2008-2015) period. The carbon intensity is measured as the weighted average emissions per TJ of energy consumption.

To gain additional insights about the potential effects of the rising carbon tax on firm behavior and outcomes, above, the distribution of total energy consumption has shifted slightly to the right indicating a minor increase in firms' 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. Most notably, however, Figure 2 shows the distribution of total energy consumption, CO_2 emissions, and CO_2 intensity before and after the 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 firms' 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. Most notably, however, Figure 2 indicates that firms drastically reduced their carbon intensity as reflected by a distinct level shift of the corresponding distribution to the left.

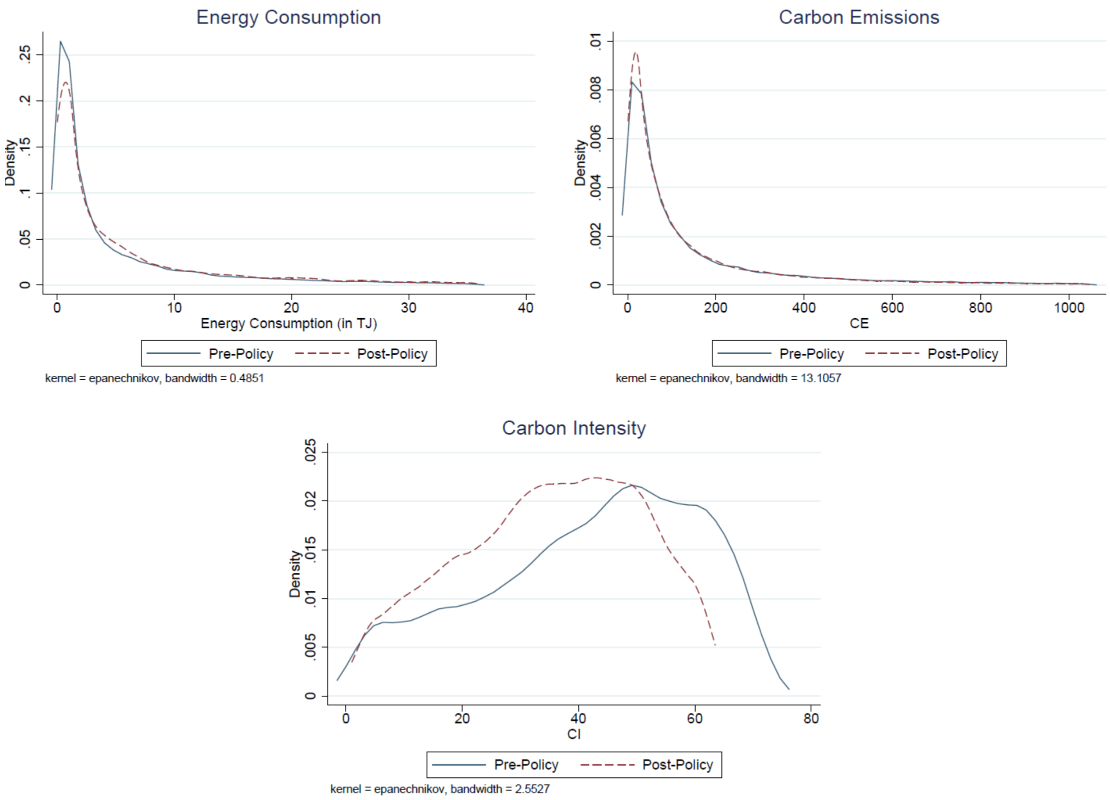

Figure 2 Density Graphs

Notes: The graphs show the empirical distribution of total energy consumption, fossil fuel emissions, and carbon intensity before (solid line) and after (dashed line) the policy change based on data from the period 2002-2015.

3.2 Carbon Emission Decomposition

In this section, we analyze how firms' consumption and emission patterns evolved between 2002 and 2015. To this end, we broke down carbon emissions into their main components: carbon intensity (*CI*) and energy consumption (*EC*). Formally, the carbon emissions CE_{it} (in tonnes of CO_2) of firm *i* at time *t* can be written as:

(1) $$CE_{it} = \sum_{j \in J} CI_j \cdot EC_{ijt}$$

where the carbon intensity CI_j of energy source *j* is defined as the tonnes of CO_2 emissions per TJ energy use and EC_{ijt} reflects the consumption of *j* (in TJ). This product was then added together over the relevant energy sources $J \in$ {light oil, natural gas, electricity} to obtain the firm-specific carbon emissions CE_{it}.[11] Equation (1) can be further decomposed as:

(2) $$CE_{it} = \underbrace{\sum_{j \in J} s_{ijt} \cdot CI_j}_{\overline{CI}_{it}} \cdot TC_{it}, \qquad s_{ijt} = \frac{EC_{ijt}}{\sum_{j \in J} EC_{ijt}}, \qquad TC_{it} = \sum_{j \in J} EC_{ijt}$$

with s_{ijt} denoting the weight of energy source *j* in a firm's energy mix and $\overline{CI}_{it}$ representing a firm's average carbon intensity.

Figure 3 below shows the index values for the carbon emissions and its components (first graph) as well as the composition of the energy mix of firms since 2002.[12] A couple of points are noteworthy: *First*, the typical firm emitted roughly 20% less carbon in 2015 than it did in 2002. A visual inspection suggests that carbon emissions respond to the tax as implied by the level shift after 2008. *Second*, the graph indicates that the lower levels of emissions were mainly achieved by significant reductions in the carbon intensity as opposed to lower energy consumption. In fact, despite the tax, the energy demand has changed little since 2002. *Third*, in Figure 3 below, the second graph illustrates "how" the reduction in the carbon intensity was achieved: As indicated by the sharp increase in natural gas and electricity consumption, firms increasingly started to substitute light oil for less carbon-intensive energy sources. However, the switch away from oil seems to have preceded the introduction of the carbon tax. The

[11] Electricity is defined as CO_2-free as it is produced by hydropower plants and nuclear power plants in Switzerland (Schleiniger et al., 2019).

[12] The base year of both indices is 2002.

question of whether the tax systematically influenced firm behavior or merely amplified existing trends is the main subject of the next section.

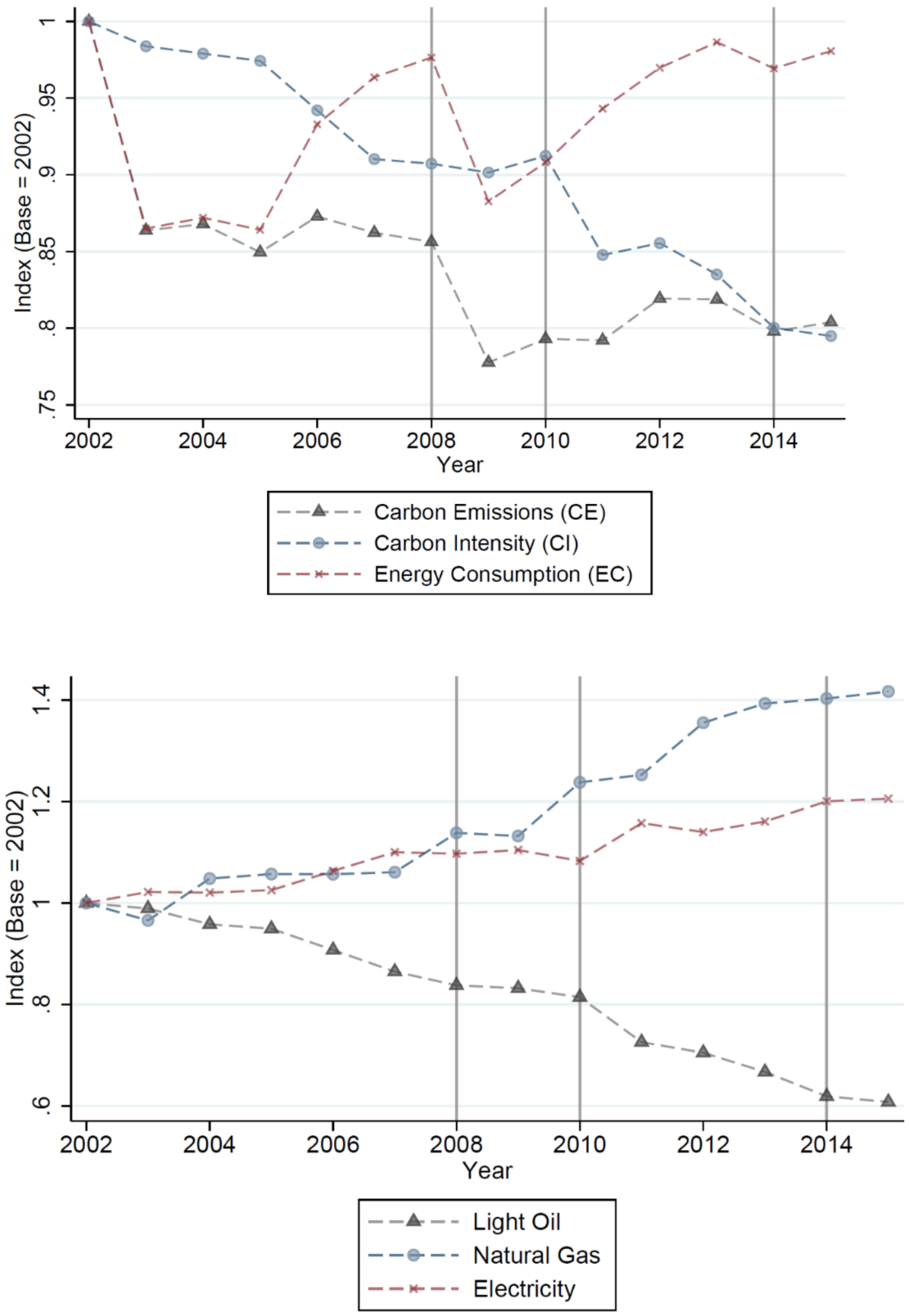

Figure 3 Development of CO_2 Emissions and Firms' Energy Mix

Notes: The first graph shows the indexed (base = 2002) CO_2 emissions, CO_2 intensity, and energy consumption. The second graph displays the share of light oil, natural gas, and electricity in the energy mix of firms.

4 The Effects of Carbon Taxes on Firm Behavior

4.1 Identification of the Carbon Tax Effect

The main goal of this study was to empirically estimate the effect of a gradually increasing carbon tax on firm energy consumption and emissions in the industry and service sectors. As mentioned above, isolating such a carbon tax effect is challenging. Besides the carbon policy, multiple channels including, e.g., changes in the economic activity, energy prices, regulation, and technological advances could potentially explain the observed consumption and emissions patterns over time.

In our main specification, we capture the carbon tax effect by estimating two-way fixed effects models of the form:

$$y_{it} = \tau_t D_t + x_{it}'\eta + A_t'\gamma + \theta_i + \lambda t + \varepsilon_{it} \quad (3)$$

where y_{it} is an energy consumption or emission indicator for firm i in year t. To capture the effect of the increasing carbon tax, Specification (3) includes a vector D_t that includes three treatment indicators that equal one in the different post-policy tax-level years.[13] θ_i is a firm fixed effect capturing time-constant, firm-specific factors such as a firm's short-term technology or willingness to invest in, e.g., renewable energy sources. Besides, we included 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.[14] Moreover, to isolate the CO_2 policy effect from observable time-varying firm-specific characteristics, we included the number of employees and the size of the floor area as controls for firm size in the vector x_{it}. Furthermore, we controlled for aggregate price, economic activity, and weather indicators subsumed in A_t.[15] Finally, ε_{it} is a classic error term capturing time-varying factors that are not observed by the econometrician, which also explains a firm's energy consumption and corresponding emission levels.

[13] Hence, the baseline is given by the pre-policy years.

[14] As a robustness check, we also estimated specifications with firm-specific time trends leading to both quantitatively and qualitatively similar results.

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

4.2 MAIN RESULTS

Table 3 below presents the effect of the rising carbon tax on total firm energy consumption, emissions, carbon intensity, as well as light oil and natural gas consumption at the intensive and extensive margins. Starting with energy consumption, we found 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 CHF 60 per tonne of CO_2, our estimates show a significant decrease of about four percent relative to the pre-policy years indicating a lagged impact of the policy on firm behavior. Although not explicitly shown in Table 3, the coefficient on the linear time trend is significantly negative, as expected, and arguably captures a generally negative trend in consumption/emissions due to technological advancements and/or other institutional changes affecting firm outcomes across all specifications and outcomes.

Turning to CO_2 emissions, our estimates indicate increasing reductions in CO_2 emissions over time as a response to the carbon tax. However, we found that the initial tax level did not induce firms to systematically cut back on emissions. With the increase in the carbon tax, emissions significantly reduced by three percent in the second and eight percent in the third post-policy period when the tax reached its maximum in the observation window. Based on the observation that the average pre-policy emission level was at a level of approximately 325 tons of CO_2 (see Table 2), the estimated policy effects are sizeable and imply reductions in the magnitude of 25 tons of CO_2 for the average firm 6-8 years after the introduction of the tax. In close connection to this, the carbon tax has induced firms to rely on cleaner energy sources as indicated by the significant decrease in the average CO_2 intensity by between 0.4 and 0.5 tonnes per TJ of energy consumed.

Table 3: Estimates of the Carbon Tax Effect

Carbon Policy Effects								
Outcome Variable	**ln(Consumption)**	**ln(Emissions)**	**Carbon Intensity**	**ln(Light Oil)**		**ln(Natural Gas)**		**ln(Electricity)**
				Ext. Marg.	Int. Marg.	Ext. Marg.	Int. Marg.	
Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$D_{2008-09}$ (12 CHF/t CO2)	0.01	-0.01	-0.45***	-0.00	-0.00	0.01*	-0.03	0.02**
	(0.01)	(0.01)	(0.16)	(0.01)	(0.02)	(0.00)	(0.03)	(0.01)
$D_{2010-13}$ (36 CHF/t CO2)	-0.00	-0.03**	-0.40**	-0.01*	-0.05**	0.01**	-0.02	0.01
	(0.01)	(0.01)	(0.17)	(0.01)	(0.02)	(0.00)	(0.03)	(0.01)
$D_{2014-15}$ (60 CHF/t CO2)	-0.04***	-0.08***	-0.55**	-0.02**	-0.11***	0.01	-0.05	-0.03**
	(0.01)	(0.02)	(0.25)	(0.01)	(0.03)	(0.01)	(0.04)	(0.01)
Firm Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic Activity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations	49,390	49,390	49,390	49,390	35,263	49,390	20,510	49,390
Number of Firms	9,833	9,833	9,833	9,833	7,422	9,833	4,333	9,833

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

To visualize the previous results, Figure 4 depicts the counterfactual and actual evolution of energy consumption and CO_2 emissions before and after the policy change.[16] As displayed in the graph on the left, 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 graph on the right 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 firm emission increases as the counterfactual and actual emission paths diverge over time.

Figure 4 *Counterfactual Plots.*

Notes: The graph shows the counterfactual and actual paths of average (log) total energy consumption, carbon emissions, and carbon intensity. Counterfactuals are constructed based on Specification (1) (see Table 3) by switching off the tax for all units in the post-policy period.

A key question that arises at this point of the analysis is how the emission reductions were achieved. We thus address the following two substantive questions:

a) Does the carbon tax induce firms to substitute more-carbon-intensive energy sources for less-carbon-intensive ones?

b) What is the carbon tax effect on the amount consumed of specific energy sources?

[16] The counterfactual path is constructed based on the estimates from the described Fixed Effect specification by switching off the policy indicators for all firms and subsequently generate predictions for each outcome for all post-policy periods.

To this end, we estimated the effect of the policy change on the consumption of light oil, natural gas, and electricity both at the extensive and intensive margins (see Table 3 for details). *First,* our estimates show that while the likelihood of consuming carbon-intensive light oil decreased by about one to two percentage points, the propensity to opt for natural gas increased by roughly two percentage points indicating substitution as a result of the tax. *Second,* at the intensive margin, we found evidence for an increasingly negative impact of the rising carbon tax on light oil consumption. In particular, we estimated that the average firm significantly reduced the consumption of light oil by five percent in the second and up to 11 percent in the third post-policy period. 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. Taken together, the overall reduction in carbon emissions for the average firm can be explained by a reduction in carbon intensity based on cutbacks in light oil consumption and the substitution of light oil with less carbon-intensive natural gas.

4.3 EFFECT HETEROGENEITY BY SECTOR AFFILIATION

In this section, we explore the potential heterogeneity in response to the introduction of the gradually increasing carbon tax between firms in the industry and service sectors. The corresponding results are summarized in Table 4.

As for the total energy consumption, our estimates indicate significant reductions in the service sector. At the same time, we found no evidence for a response to the tax among plants in the industry sector, which implies that the main findings outlined above are driven by the service sector. Similarly, firms in the tertiary sector showed a more pronounced emission response to the carbon tax across all post-policy periods than the industrial sector, which is also reflected in the size of the carbon intensity reductions. Specifically, the average firm in the service sector tended to decrease emissions by approximately nine percent when the tax was increased to CHF 60 per ton of emissions and only by six percent in the industry sector. Given the substantially higher average level of emissions in the industry sector of about 450 tonnes of CO_2 before the introduction of the carbon tax, the emissions reductions amounted to roughly 30 tonnes in the third post-policy period for a typical firm in the industry sector. This level thus clearly exceeds the one in the service sector of below 20 tonnes.[17]

The next block of estimates provides evidence for substantial effect heterogeneity between the two groups as we found significant reductions in the propensity to opt for light oil, as well as in the amount consumed: While the negative response of firms in the industry sector intensified over time both at the intensive and extensive margins, firms in the tertiary sector exclusively reduced their level of light oil consumption. In numbers, while the average firm in the industry sector reduced its light fuel consumption by about eight percent in the second post-policy period, the response to the increasing carbon tax grew to a reduced level of about 13 percent in the third post-policy period. Similarly, the likelihood of opting for light oil significantly increased by one to three percentage points in the industry sector.

In sharp contrast to this finding, our estimates indicate a strongly negative and an 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 firms in the industry sector seem to significantly apply fuel switching by opting for natural gas as a response to the tax, indicating that the substitution of light oil with natural gas described above can be attributed to the industry sector.

In conclusion, the introduction of the carbon tax has indeed led to the described overall reductions in CO_2 emissions in both sectors. However, while the typical firm in the industry sector achieved the reductions by cutting back on light oil and substituting light oil for natural gas, the average firm in the service sector mostly reduced its emissions by burning less of both fossil fuels.

[17] Since the sample roughly contains a 50-50 mix of firms in both sectors, our estimates imply an overall reduction in emissions of about 25 tons for the average firm in the sample, which closely resembles our main findings from above.

Table 4: Heterogeneity by Sector Affiliation

Carbon Policy Effects by Sector Affiliation																
Outcome Variable	**ln(Consumption)**		**ln(Emissions)**		**Carbon Intensity**		**ln(Light Oil)**				**ln(Natural Gas)**				**ln(Electricity)**	
							Ext. Marg.		Int. Marg.		Ext. Marg.		Int. Marg.			
	Industry	Services	Industry	Services	Industry	Services	Industry	Services	Industry	Services	0.01*	0.01	Industry	Services	Industry	Services
$D_{2008-09}$ (12 CHF/t CO2)	0.04***	-0.02*	0.02	-0.04**	-0.36	-0.49**	-0.01	-0.00	-0.02	0.01	(0.01)	(0.01)	0.06	-0.08**	0.05***	-0.00
	(0.01)	(0.01)	(0.02)	(0.02)	(0.23)	(0.23)	(0.01)	(0.01)	(0.02)	(0.03)	0.02**	0.00	(0.04)	(0.04)	(0.01)	(0.01)
$D_{2010-13}$ (36 CHF/t CO2)	0.02	-0.02**	-0.01	-0.04**	-0.45*	-0.31	-0.01*	-0.00	-0.08***	-0.01	(0.01)	(0.01)	0.05	-0.07**	0.03**	-0.02
	(0.01)	(0.01)	(0.02)	(0.02)	(0.24)	(0.25)	(0.01)	(0.01)	(0.03)	(0.03)	0.02**	-0.00	(0.04)	(0.03)	(0.01)	(0.01)
$D_{2014-15}$ (60 CHF/t CO2)	-0.02	-0.05***	-0.06**	-0.09***	-0.40	-0.69*	-0.03**	-0.01	-0.13***	-0.09*	(0.01)	(0.01)	0.03	-0.11**	-0.03	-0.03
	(0.02)	(0.02)	(0.02)	(0.03)	(0.34)	(0.36)	(0.01)	(0.01)	(0.04)	(0.05)	Yes	Yes	(0.06)	(0.05)	(0.02)	(0.02)
Firm Fixed Effects	Yes	Yes	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	Yes	Yes
Firm Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic Activity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	23,026	26,364	Yes	Yes	Yes	Yes
Number of Observations	23,026	26,364	23,026	26,364	23,026	26,364	23,026	26,364	17,795	17,468	4,034	6,003	8,066	12,444	23,026	26,364
Number of Firms	4,034	6,003	4,034	6,003	4,034	6,003	4,034	6,003	3,304	4,256	0.01*	0.01	1,497	2,921	4,034	6,003

Notes: Fixed effects estimates of the carbon tax on firm outcomes stratified by sector affiliation. The first (second) column for each outcome variable shows the parameter estimates for the industry (service) sector. Standard errors clustered at the firm level in parentheses: *** p < 0.01 ** p < 0.05 * p < 0.1.

5 THE CARBON TAX ELASTICITY

In the next step of the analysis, we disentangle the reaction of firms to carbon tax changes from reactions due to changes in fossil fuel prices (i.e., prices for light oil and natural gas). These considerations allowed us to provide fuel-specific estimates of the tax elasticity (based on Marion & Muehlegger (2008); Li et al. (2014)).

5.1 ESTIMATION OF TAX ELASTICITY

We started by rewriting the tax-inclusive gross price p^B as the sum of the net price p and the tax per unit of fossil fuel T (1 kW of natural gas or 100 liters of light heating oil):

$$p^B = p + T = p(1 + \frac{T}{p}).$$

By factoring out the net price and taking logs, we decomposed 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 formed the basis for the following equation:

(4) $$ln(y_{it}) = \alpha ln(p_t) + \beta ln\left(1 + \frac{T_t}{p_t}\right) + x_{it}'\eta + A_t'\gamma + \theta_i + \lambda t + \varepsilon_{it}$$

where $\ln(y_{it})$ denotes firm consumption of light oil or natural gas. Importantly, Equation (4) 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 included an aggregate linear time trend t intended to capture technological and institutional developments in all specifications; x_{it} is a vector of time-varying firm characteristics; A_t contains aggregate economic activity and weather indicators and θ_i is a firm fixed effect. Given its relatively small size, we assumed that Switzerland can be regarded as a price taker that does not affect world market prices of fossil fuels. Moreover, we also controlled for annual temperature patterns, the business cycle, and firm size measures that may be correlated with local fossil fuel prices through the demand side. At least after controlling for these factors, fossil fuel prices were assumed to be exogenous from the perspective of operating firms.[18]

As mentioned above, the tax elasticity is related to the parameter β. We first took the derivative of Equation (4) concerning the carbon 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 carbon tax. This semi-elasticity must be multiplied by the tax to arrive at the final carbon tax elasticity of light oil/natural gas consumption:

$$\frac{\partial ln(y)}{\partial T} T = \frac{\partial ln(y)}{\partial lnT} = \beta \frac{T}{p+T} \quad (5)$$

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, carbon taxes must be fully passed on to consumers, which corresponds to a complete pass-through of the carbon tax to gross prices. Due to the short tax series, we were not able to test this assumption empirically. However, an exogenously fixed world market price for fossil fuels for Swiss consumers would imply that carbon taxes are fully borne by domestic consumers. In addition, Marion and Muehlegger (2011) and Li et al. (2014) provided 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.

5.2 ELASTICITY ESTIMATES

Table 5 below presents the estimated parameters from Equation (4). In line with the results in Li et al. (2014), we observed that firms tend to respond more strongly to the tax than to the tax-exclusive net price as the magnitude of the estimated β's (second row) are consistently larger than the estimated α's (first row)[19] for both types of fossil fuels. An explanation might be that

[18] We also took into account the greater precision of OLS estimates for the elasticity derivation compared to less precise IV estimates.

[19] This can be seen when taking the derivative of Equation (4) with respect to the tax-exclusive net price to obtain the following price semi-elasticity: $\frac{1}{p}\left(\propto - \beta \frac{1}{p+T}\right)$. The tax semi-elasticity $\beta \frac{1}{p+T}$ is larger than the price semi-elasticity whenever $\beta > \alpha$.

firms perceive the carbon tax as permanent as opposed to fossil fuel prices that exhibit a substantial amount of "natural" variation over time. This can be seen in Figure 5 which plots the gross and net prices of heating light oil (left graph) and natural (right graph) over time. Moreover, we found that the two sectors' response to the tax on light oil consumption did not differ (cf. Specification 5 and 6): the typical firm in both sectors shows essentially no response to changes in the net price of fuels but a significant and sizeable reaction to changes in the tax. In contrast, the industry sector does not show a significant tax response in their natural gas consumption, whereas firms in the service sector respond strongly to the tax (cf. Specification 7 and 8).

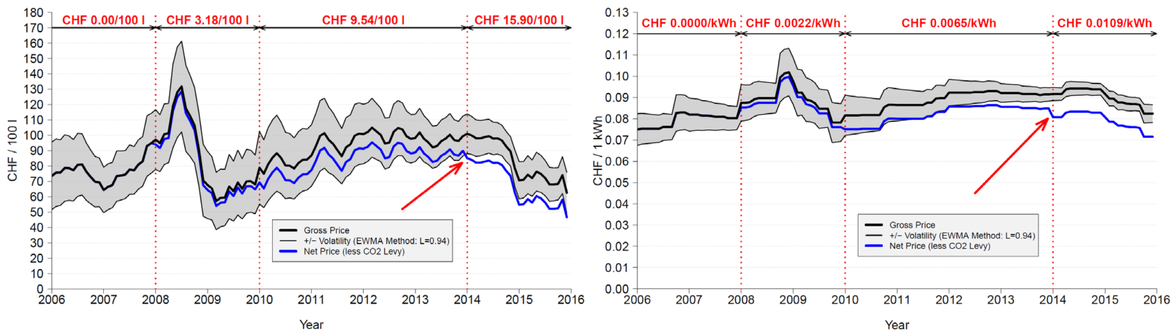

Figure 5: Price Charts of Light Oil and Natural Gas

Notes: The figure shows the gross prices (black) and net prices (net of carbon tax) prices (blue) of heating light oil (left panel) and natural gas (right panel).

In the next step of the analysis, we computed the tax elasticity of light oil using the result from Equation (5) based on the estimated βs from Specifications (1) and (2) in Table 5. To this end, we required a value for the share of the carbon tax relative to the gross price $\left(\frac{T}{p+T}\right)$ to calculate the tax elasticity. The corresponding tax fraction of the gross price rose from three percent in 2008 to about 20 percent in 2015, which indicates a stronger tax "signal" over time. Employing a 20 percent tax share leads to a tax elasticity estimate for light oil consumption of between -0.06 and -0.17. In other words, our estimate implies an inelastic demand curve for which a one percent increase in the carbon tax is associated with a decrease in the light oil consumption of up to 0.17 percent.

As for the calculation of the tax elasticity of natural gas consumption, we used the tax-gross price ratio of natural gas in 2015 which amounted to 15 percent. This resulted in tax elasticities of between 0.18 and -0.1 for natural gas. An interesting finding in this context is that while firms in the service sector showed a significant tax response (implied elasticity of -0.19), the tax did not affect the natural gas consumption decision of firms in the industry sector (see

Specification 8). This finding also resonates with a previous result shown in Table 3, namely that the reductions in natural gas consumption in the post-policy period were mainly realized by firms in the service sector.

Table 5: Tax Elasticity Estimates

Outcome Variable	**ln(Light Oil)**		**ln(Natural gas)**		**ln(Light Oil)**		**ln(Natural gas)**	
Sectors	Industry & Services				Industry	Services	Industry	Services
Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(net light oil price, pre-tax)	-0.26***	-0.02			0.03	-0.08		
	(0.04)	(0.02)			(0.03)	(0.05)		
$\ln(1+\frac{tax}{\text{net light oil price}})$	-0.85***	-0.33**			-0.25**	-0.47**		
	(0.26)	(0.14)			(0.13)	(0.22)		
ln(net natural gas price, pre-tax)			-0.00	-0.08			0.14	-0.22
			(0.21)	(0.13)			(0.19)	(0.18)
$\ln(1+\frac{tax}{\text{net natural gas price}})$			1.24*	-0.67**			0.21	-1.30***
			(0.68)	(0.34)			(0.51)	(0.46)
Firm Fixed Effects	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Firm Characteristics	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic Activity / Weather Indicators	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Number of Observations	35,473	20,613	35,473	20,613	17,883	17,590	8,085	12,528

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

6 CONCLUSION

Ever since researchers have provided evidence for a causal link between man-made emissions of greenhouse gas and global warming, there is a broad consensus among the scientific community that actions are necessary to drastically reduce greenhouse gas emissions and avoid the dramatic consequences of climate change. However, no consensus has been reached regarding the key question of how to reduce greenhouse gas emissions efficiently. In fact, a broad spectrum of climate policy instruments is in use concurrently, ranging from emission trading schemes, subsidies for renewable energy to target agreements, as well as taxes on CO_2 emissions. Most environmental economists agree that, given that climate change has caused more than one market failure, it is justified to apply more than one instrument and that a pricing instrument is part of this policy mix (Goulder, L., Parry, I. W., 2008). This is also reflected by the fact that more than 46 governments worldwide have adopted some form of pricing (World Bank, 2020a). However, there are still major emitters, such as the US, that continue to dispute the theoretical advantages of price versus quantity instruments instead of implementing policies to reduce greenhouse gas emissions (Stavins 2019).

In practice, the literature on taxes has suggested that tax rates have often been too low to have a significant impact on consumption patterns, that they have not been adjusted over time and have, therefore, been ineffective, or that the effects may have been lost in the “noise” of fossil fuel price changes (Haites et al., 2018). In contrast, emissions trading schemes have suffered from lax caps or the use of offsets, which has led to low prices. The most effective price policies have been hybrid schemes such as the emissions trading scheme in the UK, which has introduced a minimum CO_2 price and has achieved the fuel switch from coal to gas (Kosch & Abrell, 2020).

This paper contributes to the small empirical strand of the literature on carbon price evaluation (Andersson (2019), Aghion et al. (2016); Li et al. (2014); Murray & Rivers (2015), Sterner (2015); Rivers & Schaufele (2015); Sterner (2015); Martin et al. (2014a); Davis & Kilian (2011); Bjørner & Jensen (2002)) by empirically examining the effect of one of the world’s highest CO_2 prices,i.e., the Swiss carbon tax, rather a hybrid instrument that follows the approach of Baumol and Oates (1971) as it combines price and quantity features.

Using firm-level data for the period 2002-2015, we studied the effect of the introduction of an increasing carbon tax on energy consumption and carbon dioxide emissions of firms active in the service and industry sectors in Switzerland. The Swiss setting offered us a unique opportunity: We were able to observe the reaction of firms exposed to a high carbon tax as it was drastically increased by as much as 400 percent between 2008 and 2015. Our results provide evidence for a significant reduction of eight percent of firms' carbon emissions, as well as reduced levels of energy consumption by as much as four percent for the typical firm when the Swiss carbon tax was at CHF 60/t CO_2. Our findings support the literature which has claimed that only high carbon prices will be effective in reducing CO_2 emissions (Haites al, 2018).

Moreover, we showed that there is considerable heterogeneity in how emission reductions are realized across sectors: While we observed reductions in fuel consumption in both the industry and the service sectors, we also found extensive margin responses as firms in the industry sector increasingly substituted light oil with natural gas as a less carbon-intensive alternative to power economic activity. Thus, our findings are in line with the literature which has shown that CO_2 price instruments mainly lead to fuel switches (Kosch & Abrell 2020). For the service sector, the general decrease in fuel consumption reported is likely driven by factors such as investments in better building insulation or more efficient gas heating systems. Finally, our analysis revealed that firms in both sectors hardly respond to changes in the net price of fossil fuels. Instead, they reacted to the tax itself: We estimated tax elasticities for light oil consumption of up to -0.17 and -0.10 for natural gas, the latter being mainly driven by firms in the service sector. The fact that the reaction is stronger to changes in the tax rate than to changes in energy prices is consistent with other research (Andersson, 2019; Li et al., 2014; Rivers & Schaufele, 2015) and may best be explained by the fact that the price signal established by the tax is less volatile than that of net prices (see Figure 5).

Overall, our findings give new insights into the interplay between CO_2 pricing and firm behavior along several dimensions demonstrating their effectiveness in inducing firms to reduce their CO_2 emissions and switch to less carbon-intensive alternatives. Thus, our results are relevant not only for the academic community but also for policymakers intended to design effective climate policy instruments. However, to be able to achieve net-zero emissions by 2050, much more ambitious reductions are necessary, including incentives to invest in negative emissions technologies. Whether price instruments can deliver such ambitious targets, and what they will look like in a net-zero world is a worthwhile area for future research.

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