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# The Effect of the Swiss $CO_2$ Levy on Heating Fuel Demand of Private Real Estate Owners

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**Abstract:** To effectively mitigate climate change, it is crucial to better understand the reaction of fossil-fuel demand to price and tax changes, and more precisely to climate policy instruments such as a carbon levy. The Swiss $CO_2$ levy on heating fuels was introduced in 2008 at CHF 12/t$CO_2$eq, and was increased steadily up to CHF 84/t$CO_2$eq during the period of 2016/2017. This paper investigated the effectiveness of the levy as an instrument to reduce heating fuel demand, and hence carbon emissions, of private real estate owners. The Swiss Household Budget Survey 2006–2017 constituted the main data source. Before–after and pseudo-panel regressions were used to capture the $CO_2$ levy's effects, and a large set of household characteristics, as well as climatic conditions, were controlled for. No significant effects in the first two policy periods of 2008–2013 were found. Over the period of 2014–2017, a significant reduction in house owners' heating fuel demand of up to 14% with respect to 2006–2007 was detected. The effect was less significant and smaller in magnitude for flat owners. A significant $CO_2$ levy semielasticity of heating fuel demand of −1.3% for house owners was further estimated. Hence, the results confirmed the effectiveness of the $CO_2$ levy under the conditions that the levy was sufficiently high, as during the years of 2014–2017, and households directly paid the levy and were responsible for decisions concerning heating and insulation, as was the case for house owners.

**Keywords:** carbon tax; energy consumption; fossil fuel; policy evaluation; price elasticity; tax elasticity; household panel; pseudo-panel; Switzerland

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## 1. Introduction

The annual mean temperature has risen by 2 °C in Switzerland since 1864 [1], which is about twice as much as in the rest of the world during the same period. Both the population and biodiversity are highly exposed to global warming: dryer summers, changes in water flow rates, increased frequency of extreme events such as heavy precipitations or heat waves, pests and new diseases, and even water scarcity are just a few among the numerous expected impacts [2].

In addition to adaptation measures, taking action against global warming is urgent, and the international community agreed to limit the average global warming to well below 2 °C compared to the preindustrial era under the Paris climate agreement in 2015 [3].

To effectively mitigate climate change, it is crucial to better understand the reaction of fossil-fuel demand to price and tax changes, and more precisely to climate policy instruments such as a carbon levy. Measuring the effects of carbon taxation is of main importance for acceptance and efficiency of climate policy. Further research is asked for in papers, such as that by Hayek et al. [4]. Switzerland offers a nice setting in this sense, as the carbon levy was introduced in 2008 and has been increased steadily thereafter. The present paper estimates, and hence provides, quantitative results on the reactivity of households with respect to price and tax changes in the very relevant domain of heating fuels.

Switzerland's main long-term goal is to reach carbon neutrality by 2050. The Federal Council [5] recently adopted the corresponding "Long-Term Climate Strategy for Switzerland". The strategy set out climate-policy guidelines up to 2050, and established strategic targets for key sectors, building on the revised $CO_2$ Act. Approved by Parliament in autumn 2020 and due to come into force in 2022, the implementation of the Act is a key prerequisite to achieving long-term climate targets. It should put Switzerland on track to reduce greenhouse gas emissions by 50% by 2030 and reach net zero by 2050. As the facultative referendum was requested, the Swiss population voted on the revised $CO_2$ Act in June 2021 and rejected the Act. (The facultative referendum is an instrument from the direct democracy that allows an opposition from the population to the entry into force of a new law by submitting it to a referendum. Any citizen can, within a period of 100 days, collect 50,000 signatures from Swiss citizens to ask for a popular vote on the introduction of the law.). Further policy steps now have to be defined, and empirical evidence on the effects of climate policies is needed even more. The possibility of increasing the $CO_2$ levy on heating fuels from CHF 96/t$CO_2$eq up to CHF 210/t$CO_2$ and of introducing a higher price for transport fuel were the main arguments against the revised $CO_2$ Act.

In 2018, the housing sector emitted 7.7 million t $CO_2$eq, which represented around 17% of total emissions in Switzerland [6]. It is the second-largest emitter, just after the transport sector. Since 2008, a set of instruments has been used to curb emissions. Overall, the building stock in Switzerland has reduced its $CO_2$ emissions at a rate of 0.6 t per year since 2010 [6]. The $CO_2$ levy on heating fuels is the main policy tool. (Market-based policies such as carbon taxes are widely seen as a very cost-efficient approach by economists to fight climate change [7]. Braungardt et al. [8] stated that for the buildings sector in Germany, carbon pricing has a reinforcing effect and adds to the consistency of the policy mix.) Since 2008, Switzerland has imposed a levy on fossil heating fuels; i.e., light oil and natural gas [6]. (The Swiss $CO_2$ levy only applies to light oil and natural gas, and not to $CO_2$ emitted by other sources.) The main goals are to incentivize all economic agents to choose less-carbon-intensive fuels, and to encourage a more rational and economic use of fossil fuels. Initially set at a level of CHF 12/t $CO_2$eq in 2008, it was subsequently raised several times because the reduction targets set in the $CO_2$ Act were not met (see Table 1). For the period 2018–2020, a levy of CHF 96/t $CO_2$eq was applied. This was a relatively high levy in an international comparison [9]. There are no levy exemptions for households. (Greenhouse-gas-intensive installations can be exempted from the $CO_2$ levy if they commit to a reduction in their greenhouse gas emissions in return. Operators of large emission-intensive installations that participate in the emissions-trading scheme are also exempted from the $CO_2$ levy.) To reduce the burden of the levy, they must reduce their fossil heating fuel consumption; for example, via lower room temperatures, through the renovation of their house or flat, or by installing low-carbon heating systems such as heat pumps [10]. (In Switzerland, a large majority of residential buildings are still heated by fossil fuels [11]. In 2017, 39% of Swiss residential buildings had a light oil heating system, 21% had a central heating system with gas, 18% used a heat pump, 10% used wood, 7% used electricity, and 4% used district heating. The remaining 1% of residential buildings used other energetic agents, solar collectors, or no heating system.)

About two-thirds of the revenues from the $CO_2$ levy were redistributed to the population (per capita) and firms, while the other third (max. CHF 450 million) was allocated to energy-efficient renovations of buildings (buildings program), as well as to a technology fund [12]. The buildings program has been active since 2010, and in addition, is financed by cantonal funds. It encourages energy-saving renovations of buildings by granting subsidies and imposing cantonal energy standards [12]. The implementation of the program is under cantonal responsibility; however, some coordination among cantons is taking place. (Switzerland is organized as a federal state, in which the 26 cantons have important responsibilities in the building and energy domains.) In coherence with Zhang et al. [13], a carrot-and-stick policy was implemented (subsidies and levy), and local particularities were taken into account through the important roles of the cantons.

This study empirically investigated the effectiveness of the levy as a climate policy tool to reduce the Swiss residential sector's carbon emissions. This is important both for efficiency and acceptance reasons. The impact of the Swiss $CO_2$ levy on fossil heating fuel demand of both single-family house and flat owners were quantified. This is the first paper to use the official large-scale Swiss Household Budget Survey (SHBS) over the long period of 2006 to 2017 [14]. In addition to a before–after analysis controlling for as many determinants as possible, a pseudo-panel estimation [15] with cohort fixed effects was performed. The sample was restricted to house and flat owners, and hence excluded tenants from the analysis, as their hands are often tied with respect to heating-fuel-reducing activities.

**Table 1.** Swiss $CO_2$ levy rates.

| Years | $CO_2$ Levy (CHF/t$CO_2$eq) | $CO_2$ Levy on Light Oil (CHF/100 L) | $CO_2$ Levy on Natural Gas (CHF/100 $m^3$) |
|---|---|---|---|
| 2008–2009 | 12 | 3 | 2.5 |
| 2010–2013 | 36 | 10 | 7.4 |
| 2014–2015 | 60 | 15.8 | 12.4 |
| 2016–2017 | 84 | 22.2 | 17.4 |
| 2018–2020 | 96 | 25.4 | 19.8 |

Source: [16]. Note: conversion: 1 L light oil = 1 $m^3$ gas: https://www.ge.ch/statistique/tel/domaines/08/08_03/facteurs_conversion.pdf, accessed on 30 November 2020); the most recent levy period 2018–2020 could not be covered by the household sample ending in 2017.

Significant and increasing effects of the $CO_2$ levy on house owners' heating-fuel demand during the most recent two policy-periods; i.e., 2014–2017, were found. Two main factors can explain these results. First, the levy was probably too low to induce visible effects on households' behavior in the short term [17,18]. Second, households were not able to react immediately to changes in the levy, as the decision for and the installation of additional insulation or a new heating system take time [19,20]. For flat owners, the effects of the levy took more time to materialize, and were smaller and less robust. Our findings complemented and refined the existing studies on the effects of the Swiss $CO_2$ levy, which either did not find any effects of the levy [10], or found large effects since the introduction of the levy [21].

The results of disentangling the reaction to changes in heating fuel prices and the $CO_2$ levy showed that Swiss house owners reacted on average almost two times more to changes in the $CO_2$ levy than to equivalent changes in the market price. Specifically, it was found that an increase of CHF 1/100 L of the $CO_2$ levy decreased heating fuel demand by about 1.3%, while an equivalent increase in the market price of heating fuels reduced demand by about 0.7%. Xiang and Lawley [22] estimated a carbon-tax semielasticity of residential natural gas demand in British Columbia of the same order of magnitude. House owners showed a larger reaction to both the price and the levy than flat owners.

The findings of this paper can be useful to any country designing a climate-policy strategy with respect to heating fuels. The results confirmed the success of an early and soft introduction of the tax. This allowed it to gain acceptance, and provided security for medium and long-term investments. As tax rates rise over time, the incentive effect develops, and households have time to adjust over the years and take advantage of renovation cycles. The results further highlighted the relevant distinctions between flat and home owners, which are necessary to keep in mind when introducing climate policies. Clearly, every country has its own characteristics and challenges. Księżopolski K. et al. [23], for instance, highlighted the burden that spending on energy for heat puts on rural households in Poland. They argue that this must seriously be taken into account when designing public policy. While Switzerland has relatively high income levels, any policy that increases costs for households, and especially rural households, has also led to strong political opposition. Hence, the challenges to address acceptance are similar. The main findings of this paper are of international relevance, while local specificities always have to be considered in addition.

The rest of the paper is organized as follows: Section 2 reviews the relevant literature, Section 3 describes the data, and Section 4 outlines the econometric specifications. The results are presented and discussed in Section 5, while Section 6 concludes and draws the policy implications.

## 2. Literature Review

Isolating the effect of a carbon tax on residential heating fuel demand is very challenging, as other factors affect demand for heating fuels. Empirical approaches such as before–after, difference-in-difference, or synthetic control methods have been used to isolate the effects of carbon pricing from other shocks (for a recent publication, see [24]). Many papers also relied on model-based simulations. They defined a hypothetical counterfactual development path to estimate the impact of carbon pricing [21,25,26].

The degree of responsiveness of households to carbon pricing can be estimated via the semielasticities of demand, in which the price of fossil fuels is decomposed into a carbon price component and a tax-exclusive retail price (price net of carbon policy). Xiang and Lawley [22] estimated a 3% decrease in residential natural gas consumption per 1 USD cent/$m^3$ increase of British Columbia's carbon tax. They also found that the responses of households to a carbon-tax increase were much stronger than to an equivalent market-price increase. (This finding was confirmed by Rivers and Schaufele [27] for the transport sector over the period of 1990–2011. They found that the carbon tax in British Columbia reduced the short-run (i.e., over five years) demand for gasoline significantly more than an equivalent price increase.) Households are expected to react more to an increase in the $CO_2$ levy than to an equivalent increase in market prices, because they might perceive $CO_2$-levy changes to be more persistent than market-price changes [28]. In general, when calculating and comparing elasticity estimates, the time span considered is of main importance [29]. Labandeira et al. [30] found that the average light-oil price elasticity in the short term was around −0.2, while the average long-term price elasticity for light-oil demand reached −0.7. The same observation was made for natural gas, in which the short-term and long-term price elasticities were −0.2 and −0.6, respectively.

Country-level data was often used in the literature when empirically assessing the impact of carbon pricing. For instance, Lin and Li [31] used a difference-in-difference approach to estimate the effect of carbon taxation on the per capita $CO_2$ emissions of a panel of five north European countries over the period of 1981–2008. They found a significant negative impact of the carbon tax on the growth of the per capita $CO_2$ emissions of about 1.69% in Finland, and no significant impact for the other countries. According to the authors, the absence of effects for the other countries could be explained by important tax exemptions. Best et al. [32] studied a panel of 142 countries over two decades (1997–2017) and found evidence of a 2% lower average $CO_2$ growth rate in countries that had a carbon price with respect to countries with no carbon pricing.

Andersen [25] used a macroeconomic model (E3ME) to estimate the impact of carbon taxation on emissions for six European countries over the period of 1994–2003. He identified an average reduction in emissions of 3.1% as a result of carbon taxation. The effect was largest in countries with high carbon tax rates such as Sweden and Finland (5.9%). Using a general equilibrium model, Bruvoll and Larsen [26] found a reduction of 2% in $CO_2$ emissions over the period of 1990–1999 due to the carbon tax in Norway. According to the authors, the numerous tax exemptions, as well as the inelastic demand of the taxed fuels, were responsible for the absence of stronger effects. Haites et al. [9] and Haites [17] also stated that low carbon tax rates failed to materially exert a significant impact on emissions. Haites et al. [9] argued that tax rates in general are low in Europe relative to the social cost of carbon and relative to the prices of taxed fuels. In fact, only the tax rates of Sweden, Switzerland, Liechtenstein, and Finland exceeded the carbon tax level needed to respect the emissions-reduction targets set under the Paris agreement. Hence, analyzing the Swiss case was of particular interest.

Although the main bulk of studies used economy-wide data, several papers have investigated the residential sector. (For an overview covering different heating systems from a consumer perspective, including external effects and under different tax scenarios, see Karlsson and Gustavsson [33].) Filippini et al. [34] combined approaches from energy-demand modelling and frontier analysis to estimate the level of energy efficiency for the residential sector in the EU-27 member states for the period of 1996 to 2009. They found that financial incentives and energy-performance standards led to energy-efficiency improvements, whereas informative measures did not have a significant impact. Thonipara et al. [18] analyzed energy efficiency in residential buildings for 28 countries in the EU over the period of 2000–2015. They found that carbon taxation increased energy efficiency and that a carbon tax of EUR 120/t$CO_2$ reduced energy consumption markedly stronger than a tax of EUR 30/t$CO_2$. Runst and Thonipara [24] analyzed impacts of carbon taxation on the residential sector in 17 European countries over the period of 1990–2016. Using difference-in-difference regressions and synthetic control methods, they found that the increase in the carbon tax in Sweden from EUR 40 to EUR 120/t$CO_2$ in 2016 significantly reduced the yearly per capita carbon emissions by about 800 kg compared to countries without carbon tax.

The state of British Columbia in Canada introduced a carbon tax on natural gas in 2008 of CAD 10/t$CO_2$eq with annual increases of CAD 5/t$CO_2$eq, reaching CAD 30/t$CO_2$eq in 2012. Xiang and Lawley [22] and Gulati and Gholami [35] estimated the effects on residential natural gas demand using provincial-level panel data for the period of 1990–2014. Xiang and Lawley [22] used panel data regressions and a synthetic control method, while Gulati and Gholami [35] used a difference-in-difference approach. Both papers found that British Columbia's carbon tax reduced the per capita residential natural gas consumption significantly, by 7% and 15%, respectively. This was in line with Murray and Rivers [36], who found an effect of 5–15% for British Columbia.

Only a few studies have investigated the effects of the Swiss $CO_2$ levy on residential heating demand and emissions. Most of them were based on model simulations ([37]; and an update of the analysis in Ecoplan [21]). Ecoplan [21] estimated the effect of the Swiss $CO_2$ levy during the period of 2005–2015 using both time-series analysis and a general equilibrium model. The effect of the $CO_2$ levy was obtained from the deviation of the observed emissions from a constructed hypothetical emission pathway that would have occurred in the absence of the levy. They obtained a significant and increasing reduction in $CO_2$ emissions due to the levy. When taking into account long-term effects such as anticipated future levy increases, the authors found a cumulated $CO_2$ emission reduction of around 8.6 million t$CO_2$. For 2015, they identified a reduction for households of between 0.6 (3.2%, short-term effect) and 1.4 (7.2%, long-term effect) million tonnes with respect to the counterfactual. (Fauceglia et al. [38] found an estimate of the elasticity of light-oil demand with respect to the $CO_2$ levy in a range between $-0.1$ and $-0.23$ for Swiss firms. These results provided evidence for a significant effect of the Swiss $CO_2$ levy on firms over the period of 2001–2015. They used fixed effects and difference-in-difference specifications on a sample of 44,909 firms from both the industry and service sectors. They found that the $CO_2$ levy had a significant negative impact on both carbon emissions (12–15%) and energy consumption (4–6%) of Swiss plants. These reductions were primarily driven by plants with a relatively carbon-intensive energy mix, and hence were most exposed to the burden of the levy).

Using an econometric approach, Weber and Ott [10] found different results concerning the effectiveness of the $CO_2$ levy on Swiss household heating demand. They focused on the increase in the levy in 2016 from CHF 60/t$CO_2$ to CHF 84/t$CO_2$, and used data for 2016 and 2017 from the Swiss Household Energy Demand Survey. Applying a difference-in-difference approach by comparing the year before and the year after the increase in the $CO_2$ levy in 2016, and households using fossil fuels with households without fossil-fuel consumption for heating, they found no significant impact of the levy increase in 2016. They also found that the increase in the levy had no effect on the propensity to renovate, even when the sample was restricted to house owners. The authors concluded that the actual design of the levy lacked incentive power. This was in contradiction with Ecoplan [21]. According to Weber and Ott [10], the ineffectiveness of the levy resulted from the fact that people might not have been informed enough about how they were taxed. In addition, their treatment group (fossil-fuel users) contained more households that were renting than the control group (non-fossil-fuel users), which contained more homeowners. This could explain the absence of visible effects, since stronger reactions would be expected from house owners. By analyzing the year just after the increase in the levy, the estimation by Weber and Ott [10] was limited to short-term impacts. (It should also be noted that the link between buying and using fossil fuels is not direct. Households often dispose of large reservoirs that they manage in terms of use and refill. In addition, during summertime, most Swiss households turn off their heating systems, and most fossil-fuel consumption for heating purposes takes place during a few winter months. Restricting the analysis to the year after the increase in the levy can lead to a partial picture of the effective behavioral change.) Long-run impacts might actually display a much larger effect on the behaviors of households. As pointed out by Ecoplan [21], taking into account long-term effects, such as anticipations of future levy increases that influence investment decisions, can more than double the observed reductions in emissions. Hence, a lag between the increase in the levy and observed effects on heating consumption would be expected. This temporal lag was also observed in elasticity estimates, as discussed above. This discrepancy in results motivated the present paper.

Based on and extending the existing literature, this study estimated the effect of the relatively high Swiss $CO_2$ levy on fossil heating fuels. We took advantage of data from a large household survey not yet analyzed for this purpose. The value added by the present work is twofold: first, it covered a long time span that included several increases in the levy. This allowed us to cover relatively high levy rate periods and unravel longer lasting adaptation measures by households. Second, it analyzed home and flat owners separately. Flat owners have less control of their heating systems, as they usually do not buy their fuel themselves. They often pay a fee to the administration of the building, even if they own the apartment. Moreover, renovations are more complicated in a condominium than for households living in a single-family house, because usually all the owners have a common heating system and must accept any renovation project.

## 3. Data

The Swiss Household Budget Survey (SHBS), a monthly cross-sectional survey conducted by the Swiss Federal Statistical Office [14], was the main data source. (Descriptive statistics are reported in Appendix A Table A2 and discussed above.) The SHBS randomly surveyed about 250 households each month. Every participant provided detailed information on their expenditures for a whole month. The SHBS also contains a large variety of sociodemographic variables on the household, and rich information on spending for main housing. Many of these variables were used in the regressions as controls. Household spending on heating fuels from the latest bill was used to construct the dependent variable. Combining 12 yearly waves of the SHBS from 2006 to 2017 led to a repeated cross-sectional dataset with more than 38,000 households. (Data for more recent years covering the latest increase in the levy rate unfortunately could not yet be obtained from the statistical office.)

Concerning the dependent variable, it is important to note that households could use a bill not older than 5 months to answer the survey. Given that Swiss households often buy heating fuels once per year, this implied that a large majority of the respondents reported zero expenditures on heating fuel. These households were excluded from the sample. This also meant that the focus was on households with at least one fossil heating fuel component in their heating system, and the complete switch from a fossil heating system to a fossil-free heating system was not possible.

Households renting their accommodations were able to influence very little energetic renovation and changes in heating systems. Their only way to react to a $CO_2$ levy was to reduce their average room temperatures. Moreover, they might have seen the increase in heating fuel prices with large time lags in their bills, and even had difficulties in identifying the costs of heating in their total housing charges. Households renting their flat were excluded from the analysis, and only households that were owner of either a house or a flat in the form of a condominium were kept in the sample.

Finally, households with extremely high expenditures of three standard deviations above the average expenditure were excluded. The remaining 8641 households were split into two groups: single-family house owners (4254 households) and flat owners in the form of a condominium (4387 households). This separation was relevant, as the variable measuring heating-fuel expenditures was not defined in exactly the same way. (In the SHBS, heating fuel and heating expenditures are two separate variables, with the former representing heating-fuel expenditures of households living in single-family or semidetached houses, while the latter corresponded to heating expenditures of households living in flats. Although different, both variables were relevant to the analysis, as they were both correlated with variables related to heating expenditures in the literature and allowed us to compare two different groups of households.) Flat owners in the SHBS might not have reported a heating fuel value that was as precise as that for house owners, because heating expenditures could sometimes be mixed with nonapportioned spending or with other charges, which was not the case for single-family house owners.

While the total sample in the SHBS was representative of many sociodemographic dimensions for the entire Swiss population, the sample restricted to house and flat owners was clearly not representative of the Swiss population. Our analysis was based on a relatively wealthy sample with older reference persons and larger households. (Moreover, homeowners only represented about a third of the total population (11.7% house owners and 24.6% flat owners), as the large majority of the population lived in a rented flat [39].) This did not, however, limit the relevance of the results. On the contrary, the focus was on the households that were in a position to make decisions that permanently influenced fossil-fuel heating demand.

Changes in raw household expenditures as reported in the survey data were hard to interpret, since they confounded changes in quantities bought and prices. Following Weber and Ott [10] and Meier and Rehdanz [40], this study constructed and applied a fossil-fuel price index to the expenditure data. (Heating fuel expenditures from 2006 through 2017 were divided by a monthly price index that took 2005 as the reference year. The monthly energy price index was a weighted average of the Swiss Consumer Price Index (CPI) [41] for the relevant heating fuels (light oil, natural gas, and wood). Weights were year-specific in order to account for the changing importance over time [42]. Ideally, we would have used household-specific variables to condition the weighted average, such as the year of construction of the building. Unfortunately, such information on the characteristics of the building were missing in the data. To account for the fact that households could use up to 5-month-old bills, the energy price index was applied over the last 6 months (i.e., the survey month and the 5 previous months). Figure A1 in Appendix A displays the evolution of the respective fuel CPIs, as well as the resulting energy price index that was used to convert expenditures into quantities.

Heating needs directly depend on outdoor temperatures. Heating degree days (HDD), expressed as the number of degrees in a day with temperatures below 18 °C [43], were taken from the HEV Schweiz [44]. (The annual sum of HDDs for every Swiss canton available in the survey dataset were used. Since the information was available for cities and not directly for cantons, cities were matched to cantons. Due to privacy protection, the data allowed localizing of surveyed households only with respect to the eight largest cantons (Aargau, Bern, Geneva, Luzern, St. Gallen, Ticino, Vaud, and Zürich), while the households from the remaining 18 cantons were grouped together as “others”. The cities used to represent their canton were Buchs, Zollikofen, Geneva, Luzern, St. Gallen, Lugano, Pully, and Zürich. An average for the cities of Basel, Chur, Glarus, Neuchâtel, Payerne, Schaffhausen, and Sion was used for the cantons designated as “others”. This was only a rough approximation of effective HDDs relevant to the households in the sample, since the temperature varied significantly depending on the elevation above sea level and the microclimate. However, this was the best that could be taken from the data.).

## 4. Methodology

### 4.1. Before–After Analysis

In the first step, a before–after analysis was performed to capture the $CO_2$ levy's effect via the following log-linear model:

$$ln\ y_i = \beta_0 + \beta_1 CL08\text{-}09 + \beta_2 CL10\text{-}13 + \beta_3 CL14\text{-}15 + \beta_4 CL16\text{-}17 + \beta_5 X_i + \varepsilon_i \quad (1)$$

The dependent variable ln $y_i$ is the natural logarithm of heating fuel demand of household *i*. (Using the natural logarithm of the dependent variable (log-linear model) allowed us to interpret the effect of each coefficient on the carbon levy dummy as a percentage change with respect to the prelevy period. It was also useful to transform the variables with the natural log whenever the distribution included large values and when relative changes were of interest instead of absolute changes.) The four $CO_2$ levy period dummy variables allowed us to distinguish between the different levels of the $CO_2$ levy: *CL08-09* represents the first policy period from 2008 to 2009; *CL10-13*, the second policy period from 2010 to 2013; *CL14-15*, the third policy period from 2014 to 2015; and *CL16-17*, the fourth policy period from 2016 to 2017. Each coefficient $\beta_1$ to $\beta_4$ therefore represents the average effect of the respective $CO_2$ levy policy period on residential heating fuel demand with respect to the period before the introduction of the $CO_2$ levy; i.e., 2006–2007. It was necessary to distinguish between the different policy periods because the levy increased over time.

Given that over the sample period, not only $CO_2$ levy levels changed, it was crucial to control for as many other relevant variables as possible. $X_i$ is a large set of covariates including sociodemographic household characteristics and proxies that controlled for the size of the housing. The latter variables, such as income, also indirectly absorbed general technical changes. It also includes cantonal and monthly fixed effects, as well as the HDDs. $\beta_0$ and $\varepsilon_i$ denote the constant and the error term, respectively.

As pointed out by Meier and Rehdanz [40], the household composition plays an important role in explaining differences in heating expenditures: heating expenditures increase with the number of persons, children, and average age of the household and its income. They also showed the importance of weather conditions (regional HDDs). These findings guided the choice of covariates.

Even though this study attempted to control for all relevant factors, there might still have been a risk of confounding the effects of the $CO_2$ levy with other determinants of residential heating demand, which would have biased the estimates. This is why a pseudo-panel analysis was performed, as outlined in the next section.

### 4.2. Pseudo-Panel Analysis

Pseudo-panel methods are a good alternative to panel data to allow for fixed effects when only repeated cross-sectional data are available [15,45]. Using such a method allowed us to include cohort fixed effects in addition to the already-included controls and cantonal and month dummies. Deaton [45] first introduced this concept, and suggested building cohort-level data from independent cross-sections when panel data were not available. Cohorts were formed by a stable group of households sharing a common characteristic, and intracohort means were used instead of household variables (Deaton [45] defined cohorts as "a group with fixed membership individuals of which can be identified as they show up in the surveys" ([45], p. 109)).

According to Deaton and Paxson [46], pseudo-panels have many advantages over classic panel data, and for many purposes are even superior to them. As stated by Deaton and Paxson [46], the major advantage of pseudo-panels over panel data is the absence of sample attrition, which is often an issue when dealing with genuine panel data. Assuming an invariant sampling design, cohort data are not concerned with sample attrition, because they are built from new samples every year [47]. Moreover, pseudo-panels can usually cover much longer periods of time, and tend to cover substantially more units than panel data.

There was a well-known variance–bias trade-off in the literature when building the cohort data. Indeed, on one hand, forming large cohorts limited the bias of the generated estimators by having more accurate cohort means. On the other hand, the larger the cohort, the larger the loss in variability, and as a consequence, the less precise the estimators were [15]. While the size and the number of cohorts was important to obtain consistent estimates, the way cohorts were defined in the pseudo-panel was just as important. Cohorts should be defined according to a selection criterion that is observable for all individuals and that is invariant over time [15]. Following Bardazzi and Pazienza [48], the birth year of the reference person of the household was used as the selection criterion to form the cohorts. (Other criterions were tested initially to construct the pseudo-panel. The birth year of the household head as the criterion to form the cohorts was retained in order to have enough cohorts and observations per cohort.) This criterion was observable for all households, and each household could be classified exactly into one cohort [15]. In order to obtain cohorts with enough households, a 3-year age bracket (e.g., 1952–1954) was used to limit the imprecision and biased estimates. Moreover, households with a reference person born before 1930 were excluded because there were not enough observations to consistently form cohorts. The final pseudo-panel was composed of 14 cohorts observed over the sample period of 2006 to 2017. Given the small number of cohorts, results should be taken with a grain of salt.

Our pseudo-panel fixed-effects model is given by:

$$\ln\ y_{ct} = \beta_1 CL08\text{-}09_t + \beta_2 CL10\text{-}13_t + \beta_3 CL14\text{-}15_t\ + \beta_4 CL16\text{-}17_t + \beta_5 X_{ct} + \alpha_c + \varepsilon_{ct} \quad (2)$$

Where $\ln\ y_{ct}$ is the natural logarithm of the heating fuel demand of cohort c in year t. (The unit root test in the natural logarithm of heating fuel demand was performed. The null hypothesis of nonstationarity could be rejected, as the $p$-values were 0.01 for flat owners and 0.02 for house owners, respectively.) In addition to the variables already defined for the cross-sectional estimation (Equation (1)) $\alpha_c$ controlled for the cohort fixed effects (including the overall constant).

### *4.3. $CO_2$ Levy Semielasticity of Demand*

This section provides the model used to disentangle the sensitivity of households to changes in the $CO_2$ levy from the sensitivity to changes in market prices. This allowed us to measure more specifically the salience of the Swiss $CO_2$ levy and verify the hypothesis in the literature that consumers tended to react more strongly to changes in the levy than to equivalent changes in the market price. Following the decompositions by Xiang and Lawley [22], Rivers and Schaufele [27], and Li et al. [28]: the price of a heating fuel $P$ was decomposed into a tax-exclusive price component p (net price) and the $CO_2$ levy $L$; $P = p + L$.

This led to the following log-linear model:

$$\ln\ y_i = \beta_0 + \beta_1 p_i + \beta_2 L_i + \beta_3 X_i + \varepsilon_i \quad (3)$$

where $\ln\ y_i$ denotes the natural logarithm of the heating fuel demand of household $i$; $p_i$ represents the weighted average inflation-adjusted, levy-exclusive monthly price of heating fuels (i.e., light oil and natural gas); $L_i$ denotes the weighted average inflation-adjusted $CO_2$ levy; $X_i$ denotes a set of control variables; and $\beta_0$ and $\varepsilon_i$ denote the constant and the error term, respectively.

Since a distinction between the different heating fuel types was not possible in the variable used from the SHBS, a weighted average of the respective prices of light oil and natural gas, as well as a weighted average of the corresponding $CO_2$ levy, were used. (Both weighted averages (the heating fuel price and the $CO_2$ levy) were adjusted to inflation by using the Swiss Consumer Price Index (CPI) ([41]; base December 2005 = 100).) All regressions were estimated separately for house and flat owners. Figure 1 below displays a recapitulation of the different methodological steps performed.

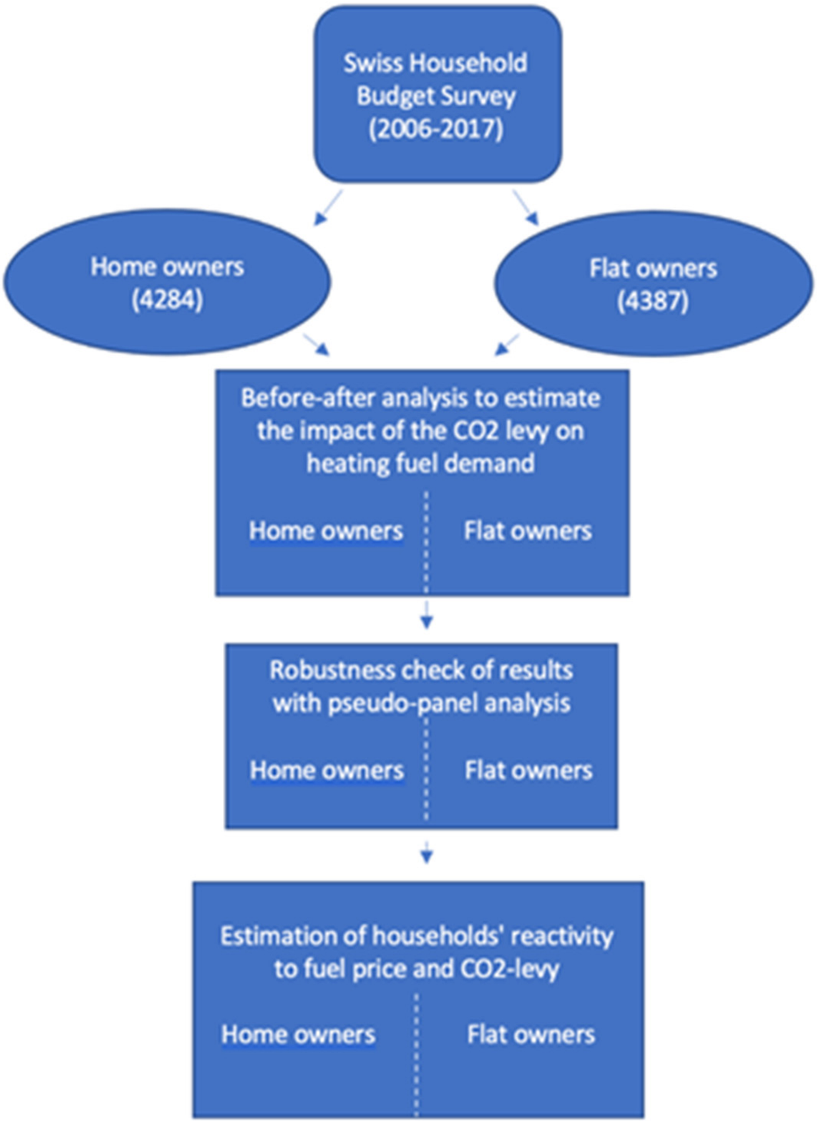


**Figure 1.** Different steps of the methodology.

## 5. Results and Discussion

### *5.1. Before–After Analysis*

In the first step, the effects of the $CO_2$ levy in Switzerland on the heating fuel demand of house and flat owners were estimated. Table 2 below reports the estimates corresponding to Equation [1] (note that small adjusted R-squared values are not unusual for household regressions in social sciences, and do not mean that the model was poor [49]). Going from column (1) to (3) for house owners and (4) to (6) for flat owners, additional control variables are introduced. Columns (2) and (5) include the main socio-demographic and climate controls such as age, income class, and temperature (natural logarithm of the sum of HDDs). Columns (3) and (6) include further household and dwelling characteristics, as well as cantonal and monthly dummies to reduce unobserved heterogeneity. Hence, the preferred specifications are presented in columns (3) and (6).

**Table 2.** Before-after analysis.

| | *Dependent Variable:* | | | | | |
|---|---|---|---|---|---|---|
| | **Log of Heating Fuel Demand** | | | | | |
| | **House Owners** | | | **Flat Owners** | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| **CL 2008-09 (12 CHF/tCO$_2$)** | −0.02 | −0.02 | −0.01 | −0.05 * | 0.01 | −0.01 |
| | (0.05) | (0.05) | (0.05) | (0.03) | (0.03) | (0.03) |
| **CL 2010-13 (36 CHF/tCO$_2$)** | −0.02 | −0.04 | −0.05 | −0.07 *** | 0.04 | 0.05 |
| | (0.05) | (0.05) | (0.05) | (0.03) | (0.03) | (0.03) |
| **CL 2014-15 (60 CHF/tCO$_2$)** | −0.05 | −0.09 * | −0.12 ** | −0.17 *** | −0.10 *** | −0.04 |
| | (0.05) | (0.05) | (0.05) | (0.03) | (0.03) | (0.03) |
| **CL 2016-17 (84 CHF/tCO$_2$)** | −0.08 | −0.12 ** | −0.14 *** | −0.15 *** | −0.17 *** | −0.11 *** |
| | (0.05) | (0.05) | (0.05) | (0.03) | (0.03) | (0.03) |
| Number of persons | | 0.08 ** | 0.07 ** | | 0.02 | 0.03 |
| | | (0.03) | (0.03) | | (0.02) | (0.02) |
| Swiss resident | | 0.16 *** | 0.14 ** | | 0.04 | 0.06 * |
| | | (0.06) | (0.06) | | (0.04) | (0.04) |
| Age | | 0.52 *** | 0.48 *** | | 0.06 | 0.05 |
| | | (0.16) | (0.16) | | (0.11) | (0.11) |
| Income class 5 | | 0.02 | 0.02 | | 0.24 *** | 0.23 *** |
| | | (0.10) | (0.10) | | (0.06) | (0.06) |
| Pro environment | | −0.03 | −0.02 | | −0.001 | 0.01 |
| | | (0.04) | (0.04) | | (0.03) | (0.03) |
| Has at least one car | | −0.10 * | 0.08 | | 0.11 *** | 0.07 * |
| | | (0.06) | (0.06) | | (0.04) | (0.04) |
| High mortgage interest | | 0.02 | 0.02 | | 0.22 ** | 0.26 *** |
| | | (0.12) | (0.12) | | (0.10) | (0.09) |
| High electricity expenditures | | 0.14 ** | 0.16 *** | | 0.14 *** | 0.14 *** |
| | | (0.04) | (0.04) | | (0.03) | (0.03) |
| Heating degree-days (log) | | 0.002 | 0.004 | | 0.02 *** | 0.01 ** |
| | | (0.01) | (0.01) | | (0.004) | (0.004) |
| Constant | 5.51 *** | 2.97 *** | 2.76 *** | 4.62 *** | 4.77 *** | 4.71 *** |
| | (0.11) | (0.75) | (0.75) | (0.02) | (0.49) | (0.49) |
| Cantonal dummies | NO | NO | YES | NO | NO | YES |
| Month dummies | NO | NO | YES | NO | NO | YES |
| Household characteristics | NO | YES | YES | NO | YES | YES |
| Heating degree-days | NO | YES | YES | NO | YES | YES |
| Socio-demographic variables | NO | YES | YES | NO | YES | YES |
| Observations | 4254 | 4254 | 4254 | 4387 | 4387 | 4387 |
| Adjusted $R^2$ | 0.01 | 0.03 | 0.06 | 0.01 | 0.08 | 0.14 |

Note: Heteroscedasticity robust standard errors are in parenthesis. Only the main explanatory variables of interest are reported here, the coefficients on the remaining variables are available in upon request, * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The coefficients with respect to the first two $CO_2$ levy periods of 2008–2009 with CHF 12/t$CO_2$ and 2010–2013 with CHF 36/t$CO_2$ were not statistically significant, neither for house nor for flat owners. This can be explained by two factors: the relatively low level of the levy (3000 L of light oil in 2008–2009 cost CHF 3270/CHF 2070, including the approximately CHF 90 from the levy.) and the possible time lag in the reactions of households to the levy. The latter effect was exacerbated for households in the flat-owner sample, as they had less influence on their heating demands, since they often did not directly buy their fuel. This missing effect in the first policy periods contradicted the simulation results by Ecoplan [21], which showed a significant negative impact of the $CO_2$ levy on residential GHG emissions directly in the first years after its introduction. Our results were more in line with those of Fauceglia et al. [38]. They found no impact of the $CO_2$ levy on Swiss firms' energy-consumption levels in the first two levy periods.

During the third and the fourth policy periods, in which the $CO_2$ levy was increased to CHF 60 and CHF 84/t$CO_2$, respectively, the results showed significant effects. For the preferred specifications in columns (3) and (6), this meant that with respect to the prelevy period of 2006–2007: for house owners, the levy led at a 5% level of significance to a 12% reduction in heating fuel demand in the period of 2014–2015, and at 1% significance to a 14% reduction in heating fuel demand in the period of 2016–2017 (the two coefficients were not statistically significantly different from each other (t = 0.3162)). For flat owners, the levy led at 1% significance to an 11% reduction in heating fuel demand in the period of 2016–2017 with respect to the prelevy period. For the previous policy period (2014–2015), the effect was not statistically significant for this sample.

An increased number of HDDs reflected colder years and significantly increased the heating demand of flat owners. Flat owners paid for more consumption based on their heating fuel, maybe even based on an HDD-index basis, while homeowners' expenditures were influenced by the management of their heating fuel stock. This might explain the different findings for flat and house owners.

Hence, the first two policy periods (2008–2013) had no visible effects on the heating fuel demand of house and flat owners. The higher levy did, however, deploy an effect during the period of 2014–2017. Heating fuel demand by house owners decreased by 12–14%, and by 11% for flat owners during the last two years of the aforementioned period compared to the prepolicy years of 2006–2007. (As an illustration, in 2015, with a tax rate of CHF 60/$tCO_2$, this led to a price increase of CHF 16 for 100 liters of light oil. A hypothetical household buying 3000 L of light oil would therefore have paid CHF 480 in $CO_2$ levy, which corresponded to 21% of the total price of CHF 2200 for this amount of light oil.)

As discussed in the Methodology section, these estimates did not allow us to control for the panel dimension. Using the best of the available data, pseudo-panel estimations are presented in the next section to mitigate these potential biases.

### 5.2. Pseudo-Panel Analysis

Table 3 displays results from the pseudo-panel fixed-effects regressions in Equation [2]. In addition to the controls used in the before–after analysis, the pseudo-panel approach allowed us to include the cohort fixed effects. However, the small number of cohorts that were in the panel should be noted, and the results should therefore be interpreted as a robustness check compared to the previous results.

**Table 3.** Pseudo-panel estimates.

| | *Dependent Variable:* **Log of Heating Fuel Demand** | | | | | |
|---|---|---|---|---|---|---|
| | *Pseudo-Panel* **House Owners Flat Owners** | | | | | |
| | **House Owners** | | | **Flat Owners** | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| **CL 2008-09 (12 CHF/$tCO_2$)** | 0.010 | 0.13 | −0.06 | 0.01 | 0.003 | −0.01 |
| | (0.13) | (0.13) | (0.07) | (0.04) | (0.04) | (0.06) |
| **CL 2010-13 (36 CHF/$tCO_2$)** | −0.01 | −0.05 | −0.11 | 0.05 | 0.04 | 0.02 |
| | (0.09) | (0.09) | (0.09) | (0.04) | (0.05) | (0.08) |
| **CL 2014-15 (60 CHF/$tCO_2$)** | −0.12 | −0.16 | −0.18 * | −0.01 | −0.02 | −0.05 |
| | (0.10) | (0.11) | (0.09) | (0.05) | (0.06) | (0.09) |
| **CL 2016-17 (84 CHF/$tCO_2$)** | −0.15 * | −0.18 * | −0.22 ** | −0.11 *** | −0.11 * | −0.13 |
| | (0.09) | (0.09) | (0.09) | (0.05) | (0.06) | (0.10) |
| Cantonal dummies | NO | NO | YES | NO | NO | YES |
| Month dummies | NO | NO | YES | NO | NO | YES |
| Household characteristics | NO | YES | YES | NO | YES | YES |
| Observations | 14 | 14 | 14 | 14 | 14 | 14 |
| Adjusted $R^2$ | 0.41 | 0.43 | 0.60 | 0.55 | 0.59 | 0.65 |

Note: All regressions include a full set of household characteristics, heating degree days and cohort fixed effects, standard errors are clustered at the cohort-level. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The pseudo-panel results for the first two policy periods were consistent with the before–after estimates we previously presented. The coefficients under all specifications were not significant, meaning that after controlling for the cohort fixed effects, no impact of the introduction of the carbon tax and its increase to CHF 36/$tCO_2$ in 2010 was observed in Swiss house and flat owners' demands for heating fuels with respect to the prepolicy period.

The previous findings were also confirmed for the fourth policy period. The effects of the $CO_2$ levy on house and flat owners' heating fuel demands were significant for the last two years (2016–2017) in the sample period, corresponding to both a longer time span since its introduction and higher levy rates. The results based on the pseudo-panel confirmed the fact that house owners had a faster and stronger reaction to the $CO_2$ levy than flat owners.

### 5.3. $CO_2$ Levy Semielasticities of Heating Fuel Demand

Table 4 presents estimates for Equation [3] for several specifications. Columns (1) to (3) and (6) to (8) were based on OLS estimates, while the following two columns use the pseudo-panel for house and flat owners, respectively. In columns (1), (4), (6), and (9) the price of heating fuels is not decomposed, assuming that consumers reacted indifferently to changes in market prices and the $CO_2$ levy. The coefficient for the price including the levy implied that a CHF 1/100 L increase in the fossil heating fuels' price decreased house owners' residential heating fuel demand by 0.7%, and flat owners' demand by 0.4 to 0.5%, This order of magnitude was consistent with the findings by Xiang and Lawley [22], who found an effect of 0.4% for residential natural gas demand.

**Table 4.** Semielasticity estimates.

| | Dependent Variable: Log of Heating Fuel Demand | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | House Owners | | | | | Flat Owners | | | | |
| | OLS | | | Pseudo-Panel | | OLS | | | Pseudo-Panel | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| **Price incl. taxes** | −0.007 *** | | | −0.007 * | | −0.004 *** | | | −0.005 * | |
| | (0.001) | | | (0.004) | | (0.001) | | | (0.002) | |
| **Net heating oil price** | | −0.007 *** | −0.007 *** | | −0.003 * | | −0.004 *** | −0.004 *** | | −0.003 |
| | | (0.001) | (0.001) | | (0.006) | | (0.001) | (0.001) | | (0.005) |
| **$CO_2$ levy** | | −0.012 *** | −0.013 *** | | −0.035 * | | −0.009 *** | −0.005 *** | | −0.024 * |
| | | (0.003) | (0.003) | | (0.013) | | (0.002) | (0.002) | | (0.013) |
| Cantonal dummies | YES | NO | YES | YES | YES | YES | NO | YES | YES | YES |
| Month dummies | YES | NO | YES | YES | YES | YES | NO | YES | YES | YES |
| Socio-demographic variables | YES | NO | YES | YES | YES | YES | NO | YES | YES | YES |
| Cohort fixed effects | NO | NO | NO | YES | YES | NO | NO | NO | YES | YES |
| Time fixed effects | NO | NO | NO | YES | YES | NO | NO | NO | YES | YES |
| Observations | 4254 | 4254 | 4254 | 14 | 14 | 4387 | 4387 | 4387 | 14 | 14 |
| Adjusted $R^2$ | 0.06 | 0.05 | 0.06 | 0.56 | 0.58 | 0.14 | 0.08 | 0.14 | 0.56 | 0.61 |

Note: All regressions include a full set of household characteristics, heteroscedasticity-robust (columns 1–3 and 6–8) and cohort-clustered (columns 4–5 and 9–10) standard errors in parenthesis, * $p < 0.1$; *** $p < 0.01$.

In columns (3) and (8), the preferred estimates with decomposed price variables and a large set of control variables are reported, while columns (5) and (10), based on the pseudo-panel, were used for their robustness check.

For house owners, a CHF 1/100 L increase in the $CO_2$ levy decreased the residential demand for heating fuels by 1.3% on average, while an equivalent increase in the market price reduced demand only by 0.7%. For flat owners, the respective effects were 0.5% and 0.4%. Hence, for flat owners again, the effects were smaller and the difference between the two was less visible. The pseudo-panel results confirmed the main findings.

The differentiated effects for market prices and levies have been observed in many studies [22,27,38,50,51]. Aversion to taxes by the population, especially toward environmental taxes, could be an explanation. Scott [50] developed a theoretical model including rational habits in gasoline demand. She showed that gasoline demand depended not only on the current price, but on the anticipated tax component of next year's price. Hence, consumers were more responsive to the relatively predictable tax-driven portion of price than to the relatively volatile before-tax price. This argument was taken up in Fauceglia et al. [38]: economic actors might regard changes in the $CO_2$ levy as permanent as opposed to fossil-fuel market-price changes that exhibit natural variation over time. Households might therefore react less to changes in market prices because they might only be temporary, while increases in the levy are fixed by the government over time and households know that they cannot avoid them.

## 6. Conclusions and Policy Implications

Reaching the reduction targets for greenhouse gas emissions set under the Paris agreement is one of the largest challenges that society is facing. If a consensus exists on the diagnosis, there is less empirical evidence and an animated political debate on the effects of climate policy instruments. Many countries have now implemented carbon prices, but often at a rate that is too low in practice to reduce emissions [9]. Further insights are asked for in the international literature; for instance, in Hayek et al. [4].

This work investigated the effectiveness of 10 years of $CO_2$ levies in Switzerland on the fossil heating fuel demand of owners of single-family houses and flats in the form of a condominium. Using the Swiss Household Budget Survey, and controlling for household heterogeneity, the results showed no significant effects of the first two $CO_2$ levy periods. This can be explained by low levy levels and the time lag needed to improve insulation and heating systems. This finding was in line with Haites et al. [9], who claimed that only high rates of carbon taxes were effective in reducing emissions. Nonetheless, for the Swiss climate policy, the introduction of a small levy was an important step, and allowed a steady increase in its level afterward, and probably a better acceptability. Our findings contradicted Ecoplan et al. [37], who simulated that the Swiss $CO_2$ levy displayed significant effects on the residential sector directly after its introduction.

During the third (CHF 60/t$CO_2$) and fourth (CHF 84/t$CO_2$) $CO_2$ levy periods, demand for fossil heating fuels by Swiss single-family households and flat owners decreased by 7% to 14% with respect to the pretax period. The results for flat owners were less significant and smaller in magnitude. Their possibilities to improve insulation or heating systems were limited, given the necessary coordination among all flat owners of a given building. These results therefore reflected expectations.

The sensitivity of Swiss households to changes in $CO_2$ levy levels was also estimated and compared to equivalent price changes in the market price of fossil heating fuels. Swiss households tended to react significantly more to $CO_2$-levy changes than to changes in the market price excluding the levy, which was consistent with the literature [22,27,28]. The results showed a carbon-tax semielasticity of residential fossil heating fuel demand of $-0.013$: a CHF 1/100 L increase in the $CO_2$ levy reduced, on average, the demand for fossil heating fuel of Swiss house owners by 1.3%, while an equivalent increase in the market price (excluding the levy) of heating fuels reduced demand only by 0.7%, which was almost two times smaller. Again, the estimated $CO_2$-levy semielasticities were smaller for flat owners.

Overall, the results suggested that policymakers should, in general, consider a $CO_2$ levy rate that is high enough to incentivize behavioral changes and renovations when implementing carbon taxation in the residential sector. In Switzerland, effects on house owners' heating-fuel demand seemed to have materialized with a $CO_2$ levy of CHF 60/t$CO_2$ (reached in 2014), which corresponded to approximately CHF 16/100 L of light oil. In 2015, the building sector reached its interim emissions-reduction target of 22% with respect to 1990, as it had decreased its emissions by 26% [2]. Our results suggested that a large part of this significant reduction can be attributed to the $CO_2$ levy. Although good progress has been made in the building sector, other sectors did not have this success; namely, the transport sector, which failed to reach its reduction target in 2015, as the $CO_2$ levy is not concerned with gasoline.

The levy in Switzerland was increased to CHF 120/t$CO_2$ in January 2022 because the reduction targets set in the $CO_2$ Act were not met. This will translate into an increase in the levy for 100 L of light oil from CHF 25.4 to CHF 31.75. Our $CO_2$-levy semielasticity estimates suggested that this increase will reduce the average demand for heating fuel by around 8.2% for house owners.

Despite significant effects, the absence of a control group limited our ability to capture the true causal incentive effect of the $CO_2$ levy. Our estimates are likely to also include the effects of the subsidies provided with the money collected via the levy. The Data did not allow us to separate the two effects, and in this sense, the incentive effect of the levy might have been overestimated. On the other hand, the complete transformation from fossil-fuel heating systems to fossil-free systems such as heat pumps are not reflected, as the corresponding data were missing. Hence, in this sense, the incentive effect from the levy might have been underestimated. Further research could develop and use a regionally and temporally differentiated index measuring other energy-policy dimensions in the buildings sector.

Although they were based on a central European high-income country, the results can provide insights for any government designing a strategy to reduce carbon emissions for heating fuels. A climate levy should be introduced early and with low rates. This would allow the simultaneous imposition of only a low short-term financial burden, and hence would benefit from higher acceptance, but also would give a clear signal that renovation and investment decisions should take into account future tax-rate increases. The levy would then deploy its effects over time and with higher levy rates. Policy makers should further be aware of the relevance of different owner structures (e.g., flat and home owners). Finally, the reaction of households to the levy is expected to be stronger than to corresponding market-price increases. Governments should take advantage of this effect and use carbon levies to fight climate change.

**Author Contributions:** Conceptualization, N.F. and N.A.M.; methodology, N.F. and N.A.M.; validation, N.F. and N.A.M.; formal analysis, N.F.; investigation, N.F.; data curation, N.F.; writing—original draft preparation, N.F.; writing—review and editing, N.F. and N.A.M.; visualization, N.F.; supervision, N.A.M.; project administration, N.F. and N.A.M. All authors have read and agreed to the published version of the manuscript.

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## Appendix A. Heating Oil Consumption and Prices in Switzerland

Light oil made up around 50% of total final heating-energy consumption by households in 2000 (see Figure 1). This share steadily decreased in the first decade of the 21st century to reach approximately 44% of total final energy consumption in 2008, when the $CO_2$ levy was introduced. This decrease continued, and reached a share of around 30% in 2017. Natural gas has experienced the reverse trend, as its share increased during the last decade, from 15% in 2000 to 20%. This reflected the transition from the more carbon-intensive light oil (0.26 $tCO_2$/100 L) to the relatively less carbon-intensive natural gas (0.2 $tCO_2$/100 L) (https://www.ge.ch/statistique/tel/domaines/08/08_03/facteurs_conversion.pdf, accessed on 30 November 2020). A hypothetical Swiss household with two adults and two children that bought 3000 L of heating fuel in 2017 paid a levy of CHF 666 for light oil or CHF 520 for gas (with the latter having a higher heating potential). (3000 L of light oil only generate 31’200 kWh, while the same quantity of gas can generate 34,200 kWh.)

Fossil-fuel prices changed over the sample period due to both changes in world market prices and the increase in the $CO_2$ levy (see Figure A2). World market prices of light oil fluctuated quite a lot, with an increase between 2009 and 2012 and a decrease thereafter, with historically low prices during the end of our sample period of 2015–2017. World gas prices fluctuated less, but also were at historically low levels over the period of 2015–2017. (Natural gas is subject to smaller price volatility compared to light oil, and therefore presents less uncertainty concerning future heating expenditures. In addition to the relatively lower carbon intensity, this is a further argument in favor of the substitution of light oil with natural gas for households.) The relative importance of the $CO_2$ levy with respect to the total price has grown significantly since its introduction in 2008. When it was introduced at CHF 12/t$CO_2$ in 2008, the price increase was negligible, as it represented only 2–3% of the total price. For light oil, it represented 10% during the period of 2010–2013, and reached 32% of the total price in 2017. (Taking again the example above, in 2017, an average house owner that bought 3′000 L of light oil for a year of heating would therefore have paid CHF 666 for the $CO_2$ levy and CHF 1701 for the other components of the price.) Thanks to the lower carbon intensity and the higher world market price of natural gas, the $CO_2$ levy represented a smaller share of the total price. This share increased from 2% to 17% [52].

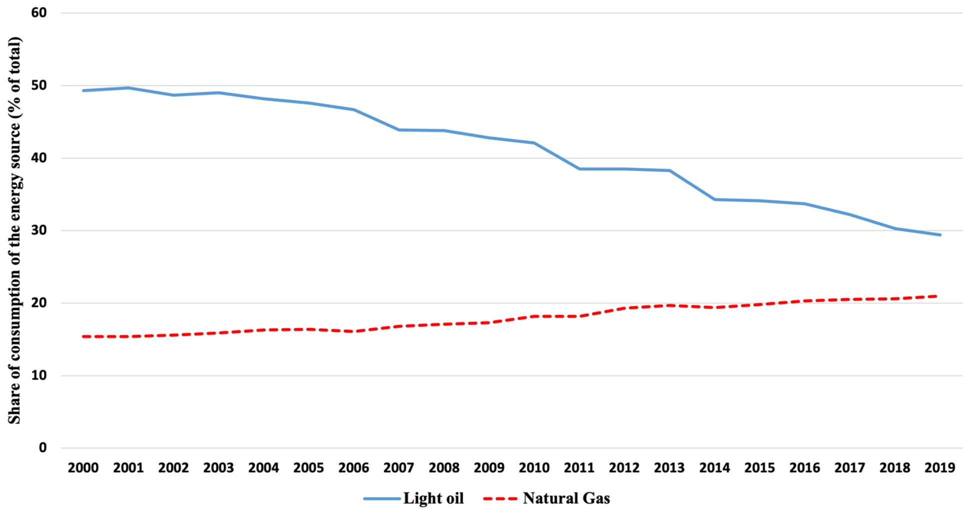


**Figure A1.** Final fossil-fuel consumption as a share of total final energy consumption used for heating (light oil, gas, coal, electricity, wood, district heating, and renewables in TJ) by Swiss households. Sources: overall energy statistics (Table 17a, [42]).

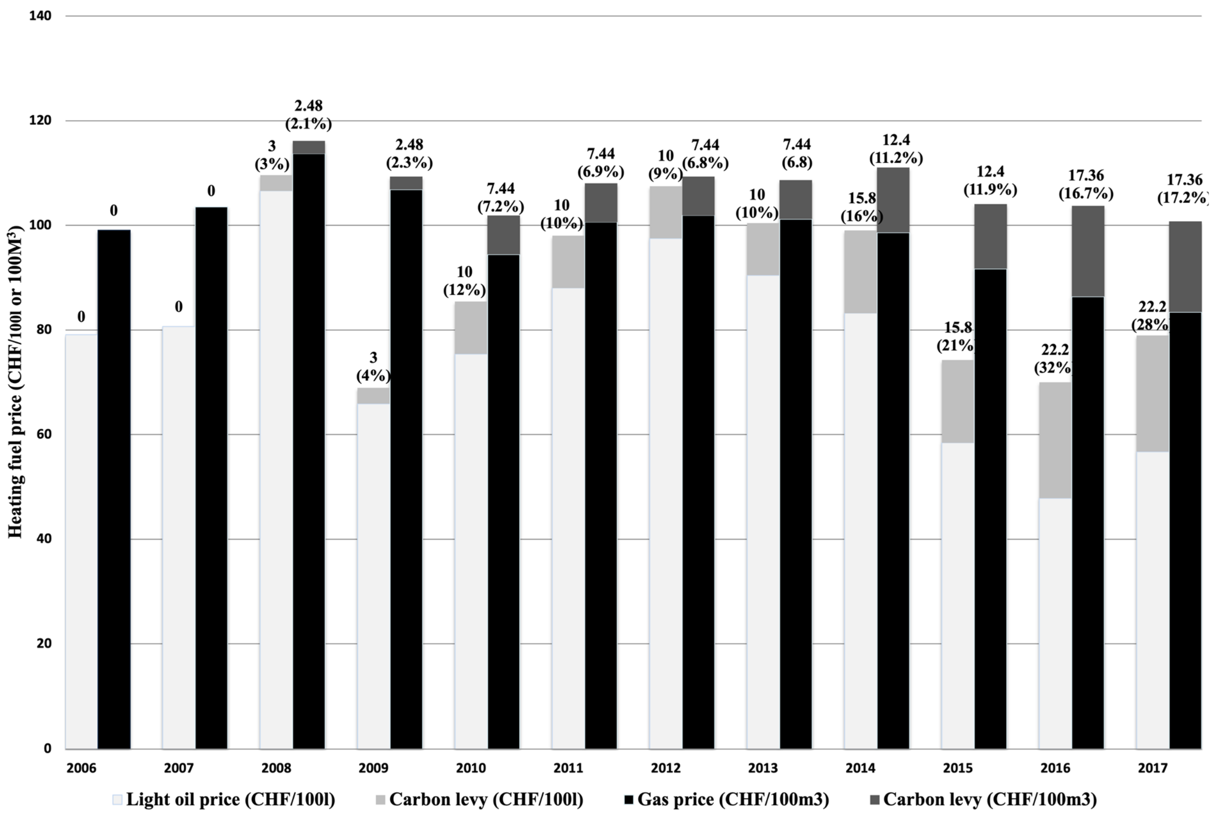


**Figure A2.** Light oil and natural gas price composition, 2006–2017. Sources: [53], own calculations.

**Table A1.** Description of variables.

| Variable | Definition |
|---|---|
| Heating fuel demand (in CHF) | Household expenditures in heating fuels transformed into quantities using an energy price index |
| Electricity (in CHF) | Electricity expenditures of the household |
| Don_env | Dummy equal to one if the household donated to an environmental association |
| Rental (in CHF) | Amount spent in mortgage interests |
| Disposable_income (in CHF) | Disposable income of the reference person in the household |
| Year | Year of the response to the survey |
| Nr_Persons | Number of persons composing the household |
| Nr_Kids_under15 | Number of children younger than 15 years old in the household |
| Nr_Persons_aged_15–24 | Number of persons aged between 15 and 24 in the household |
| Nr_Persons_aged_25–34 | Number of persons aged between 25 and 34 in the household |
| Nr_Persons_aged_35–44 | Number of persons aged between 35 and 44 in the household |
| Nr_Persons_aged_45–54 | Number of persons aged between 45 and 54 in the household |
| Nr_Persons_aged_55–64 | Number of persons aged between 55 and 64 in the household |
| Nr_Persons_aged_75+ | Number of persons aged 75 or more in the household |
| 1_person_HH | Dummy equal to one if it is a single-person household |
| Ref_person_renter | Dummy equal to one if the reference person of the household is retired |
| Ref_person_under_35 | Dummy equal to one if the reference person of the household is younger than 35 |
| Ref_person_woman | Dummy equal to one if the reference person of the household is a woman |
| Has_al_1_car | Dummy equal to one if the household has at least one car |
| Age | Age of the reference person of the household |
| ZH | Dummy equal to one if the household lives in canton Zürich |
| BE | Dummy equal to one if the household lives in canton Bern |
| LU | Dummy equal to one if the household lives in canton Luzern |
| SG | Dummy equal to one if the household lives in canton St-Gallen |
| AG | Dummy equal to one if the household lives in canton Aargau |
| TI | Dummy equal to one if the household lives in canton Ticino |
| VD | Dummy equal to one if the household lives in canton Vaud |
| GE | Dummy equal to one if the household lives in canton Geneva |
| Other_Canton | Dummy equal to one if the household lives in another canton than those previously mentioned |
| Male | Dummy equal to one if it the reference person of the household is a male |
| Female | Dummy equal to one if it the reference person of the household is a female |
| Swiss_r | Dummy equal to one if it the reference person of the household has Swiss nationality |
| Foreigner | Dummy equal to one if it the reference person of the household does not have Swiss nationality |
| HH_alone_aged_until_64 | Dummy equal to one for a single-person household younger than 65 years old |
| HH_alone_aged_from65 | Dummy equal to one for a single-person household 65 years old or older |
| HH_couple_until64_noChild | Dummy equal to one for a couple with no children whose reference person is younger than 65 years old |
| HH_couple_from65_noChild | Dummy equal to one for a couple with no child whose reference person is 65 years old or older |
| HH_alone_child | Dummy equal to one for a single person with no children |
| HH_couple_child24 | Dummy equal to one for a couple with children not older than 24 years old |
| HH_other | Other type of household |
| income_class_1 | Dummy equal to one for a household whose reference person earns less than CHF 4914 |
| income_class_2 | Dummy equal to one for a household whose reference person earns between CHF 4914 and CHF 7264 |
| income_class_3 | Dummy equal to one for a household whose reference person earns between 7265 and 9990 CHF |
| income_class_4 | Dummy equal to one for a household whose reference person earns between CHF 9991 and CHF 13,621 |
| income_class_5 | Dummy equal to one for a household whose reference person earns more than CHF 13,622 |
| high_fuel | Dummy equal to one for a household with a larger than average monthly expenditure in car fuel |
| env_fr | Dummy equal to one if the household donated a positive amount to an environmental association |
| high_water | Dummy equal to one for a household with a larger-than-average monthly expenditure in water |
| low_rent | Dummy equal to one for a household with a low monthly expenditure for mortgage interest |
| high_rent | Dummy equal to one for a household with a high monthly expenditure for mortgage interest |
| med_rent | Dummy equal to one for a household with a medium monthly expenditure for mortgage interest |
| pro_social | Dummy equal to one if the household donated a positive amount to an association |
| low_elec | Dummy equal to one for a household with a low monthly expenditure for electricity |
| med_elec | Dummy equal to one for a household with a medium monthly expenditure for electricity |
| high_elec | Dummy equal to one for a household with a high monthly expenditure for electricity |
| vhigh_elec | Dummy equal to one for a household with a very high monthly expenditure for electricity |
| HDD | Natural logarithm of the annual sum of heating degree days in the canton of the household |
| Nr_elec_furnitures | Number of fridges, tumblers, and dishwashers in the household |

Table A2 below displays the most relevant summary statistics for both groups of households. Overall, the two groups displayed similar characteristics. Real estate owners in Switzerland that responded to the survey were on average 56 years old, and a large majority were of Swiss nationality. Households in our sample were therefore older than the average Swiss resident, who is 42 years old [54] and is more likely to be Swiss: 94% of our house and flat owners are Swiss while only 75% of the population were of Swiss nationality in 2017 [54]. Households in our sample were also relatively wealthy: about half of the respondents were in the upper part of the income distribution of Switzerland, meaning that they were either in income class 4 or 5. (Income class 1 = (<4914), income class 2 = (4914–7264), income class 3 = (7265–9990), income class 4 = (9991–13,621), income class 5 = (≥13,622), [55].) Moreover, the income differences between the house and flat owners were significant. The average income for house owners (CHF 8478) was larger than that of flat owners (CHF 7482).

Another important difference between our two groups was the heating fuel demand, which was significantly higher for single-family house owners than for flat owners. Since no detailed information on the size of the housing floor was available in the data, in the regressions, we uses the number of persons living in the house, as well as the amount spent on mortgage interest (households were grouped with respect to low, medium, and high rent) and on electricity as a proxy for the size of the house or flat. Medium and high electricity consumption were dummies built with respect to the observed expenditures by households in the sample. High electricity expenditures meant monthly expenditures between CHF 90 and CHF 190. We expected that more people in the household implied more rooms to heat. The average Swiss household in 2017 was composed of 2.23 persons [56]. Our sample displayed larger households, and the differences between house and flat owners were significant: on average, 2.67 persons were living in single-family houses, while 2.47 were living in flats. The same pattern was also observed for electricity expenditures.

The dummy variable of proenvironment is equal to one if the household spent any positive amount on an environmental association during the survey month, which was the case for 12% of the house owners and 10% of the flat owners. Similarly, the dummy variable of prosocial was equal to one if the household spent any positive amount on an association.

**Table A2.** Descriptive statistics.

| | **House Owners** | | **Flat Owners** | | |
|---|---|---|---|---|---|
| **Variable** | **Mean** | **SD** | **Mean** | **SD** | **Difference** |
| Heating fuel demand (in CHF) | 202.17 | 131.84 | 111.8 | 64.31 | 90.37 * |
| Age | 56.65 | 13.45 | 56.58 | 13.42 | 0.07 |
| Male | 0.55 | 0.5 | 0.51 | 0.5 | 0.04 * |
| Swiss nationality | 0.94 | 0.24 | 0.94 | 0.24 | 0 |
| Number of persons | 2.67 | 1.24 | 2.47 | 1.19 | 0.2 * |
| Income (in CHF) | 8478.59 | 8507.56 | 7482.88 | 7915.85 | 996.37 * |
| Disposable income (in CHF) | 8278.96 | 5271.52 | 7616.83 | 4900.58 | 662.13 * |
| Income class 1 | 0.11 | 0.31 | 0.12 | 0.33 | −0.01 |
| Income class 2 | 0.14 | 0.35 | 0.16 | 0.37 | −0.02 * |
| Income class 3 | 0.19 | 0.39 | 0.21 | 0.41 | −0.02 * |
| Income class 4 | 0.25 | 0.43 | 0.25 | 0.44 | 0 |
| Income class 5 | 0.31 | 0.46 | 0.25 | 0.43 | 0.06 * |
| Prosocial | 0.27 | 0.44 | 0.23 | 0.42 | 0.04 * |
| Proenvironment | 0.12 | 0.33 | 0.1 | 0.3 | 0.02 * |
| Low rent | 0.56 | 0.5 | 0.55 | 0.5 | 0.01 |
| Medium rent | 0.43 | 0.5 | 0.44 | 0.5 | −0.01 |
| High rent | 0.01 | 0.1 | 0.01 | 0.1 | 0 |
| Electricity exp. (in CHF) | 94.12 | 57.74 | 77.8 | 47.84 | 16.32 * |
| High fuel exp. | 0.11 | 0.31 | 0.12 | 0.32 | −0.01 |
| High water exp. | 0.03 | 0.17 | 0.03 | 0.16 | 0 |
| Number of appliances | 3.03 | 1.02 | 3.16 | 1.05 | −0.13 * |
| Aargau | 0.09 | 0.29 | 0.07 | 0.26 | −0.02 * |
| Bern | 0.12 | 0.32 | 0.13 | 0.33 | −0.01 |
| Geneva | 0.02 | 0.14 | 0.03 | 0.14 | −0.01 * |
| Luzern | 0.03 | 0.17 | 0.06 | 0.24 | −0.03 * |
| St. Gallen | 0.07 | 0.26 | 0.04 | 0.02 | −0.03 * |
| Ticino | 0.09 | 0.29 | 0.14 | 0.34 | −0.05 * |
| Vaud | 0.09 | 0.29 | 0.08 | 0.27 | −0.01 |
| Zürich | 0.13 | 0.33 | 0.15 | 0.35 | −0.02 * |
| Other cantons | 0.36 | 0.48 | 0.31 | 0.46 | −0.05 * |

Note: * is a statistically significant difference between both groups.

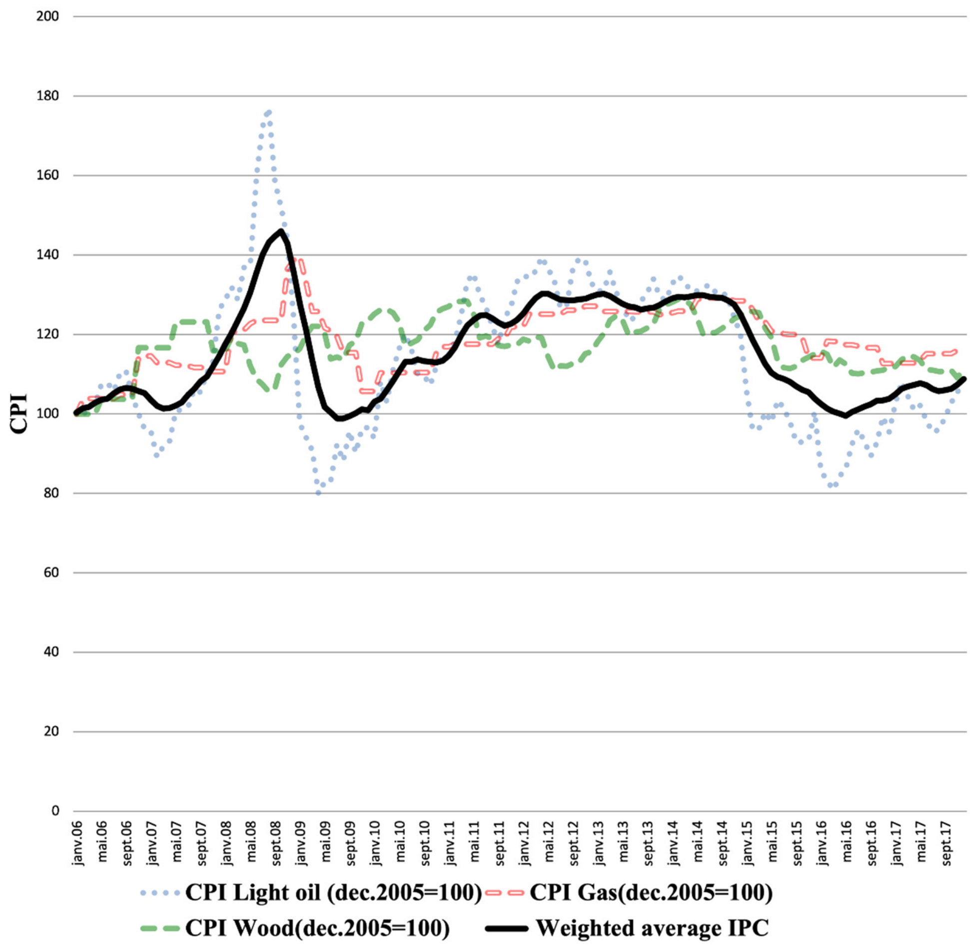


**Figure A3.** Monthly CPI and energy price index. Note: CPI, Consumer Price Index. Sources: [41,42], own calculations.

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