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Dosis Facit Effectum

Why the Scope of the Carbon Tax Matters – Evidence from the Swedish Residential Sector

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Abstract:

Sweden has gradually increased its carbon tax within the past 25 years and imposes the world's highest tax on carbon dioxide emissions today. This paper examines the impact of the Swedish carbon tax on residential carbon emissions as well as on consumer behavior. We perform Difference-in-Differences (DiD) regressions and Synthetic Control Methods (SCM) in order to evaluate the causal impact of carbon taxation on carbon emissions in the residential sector. Both methods provide evidence for a causal effect of the carbon tax augmentation in the early 2000s on residential carbon emissions. We find that the scope of the reduction of residential carbon emissions due to the carbon tax augmentation range between 200 kg (when compared to other countries with a carbon tax of more than 20 Euros implemented) and 800 kg of CO_2 per capita per year (when compared to countries without a carbon tax). Hence, the evidence points towards the effectiveness of carbon taxation in reducing residential CO_2 emissions and, thus, mitigating climate change.

JEL: Q54, P28, Q4, O38

Keywords: carbon tax, Sweden, residential building, CO2 emissions

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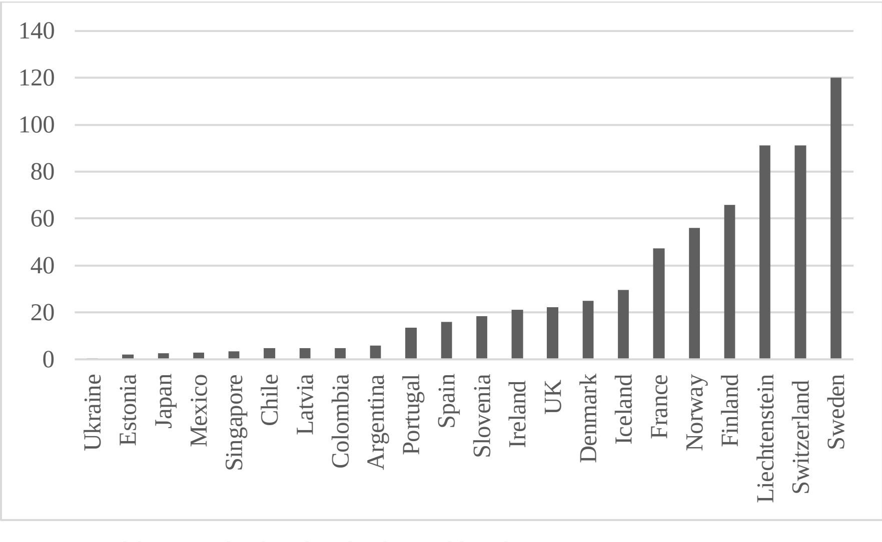
1. Introduction

As more and more countries are already affected by climate change, mitigating climate change represents one of the most urging problems on the international political agenda (United Nations 2018). The EU Roadmap to a low carbon economy aims for a reduction of residential greenhouse gas emissions reduction by 80-95% below 1990 level by the year 2050 (European Commission 2011). In order to reach these targets, member states of the European Union should make use of energy policy instruments which are effective. Previous studies found regulatory measures to be effective in decreasing residential energy consumption (Filippini et al. 2014, Ó Broin et al. 2015) and, to a lesser extent, informational campaigns and financial incentives. However, EU member states should make use of energy policy instruments that are not only effective but also efficient. There are strong theoretic arguments for the cost efficiency of carbon taxation and there is some first evidence for its effectiveness as well (Thonipara et al. 2018; Lin and Li 2011; Bohlin 1998)

While the effects of regulatory measures have been analyzed comprehensively (i.e. Levinson 2016, Filippini et al. 2014, Ó Broin et al. 2015; Thonipara et al. 2018) there is a lack of studies focusing on the impact of a carbon taxation on residential carbon emissions. Previous studies have addressed carbon taxes' effects on overall country emissions (Lin and Li 2011), their distributional effects (Renner 2018; Chapa and Ortega 2017; Parry 2015; Jiang and Shao 2014; Gonzalez 2012; Bureau 2011) or focused on scenarios (Dong et al. 2017; Elliott and Fullerton 2014; Di Cosmo and Hyland 2013; Mori 2012).

However, the effects of a carbon tax on carbon emissions of the residential sector have not been considered yet. As of 2018, there are only around 20 countries with a national carbon tax scheme, most of which set a tax of less than 25 Euros per ton of CO_2 (World Bank 2018, see figure 1). In contrast, Sweden was one of the first countries that implemented a carbon tax in the early 1990s and imposes today the highest carbon tax in the world.

Figure 1. National Carbon Tax Rates (01.01.2019, in Euros)



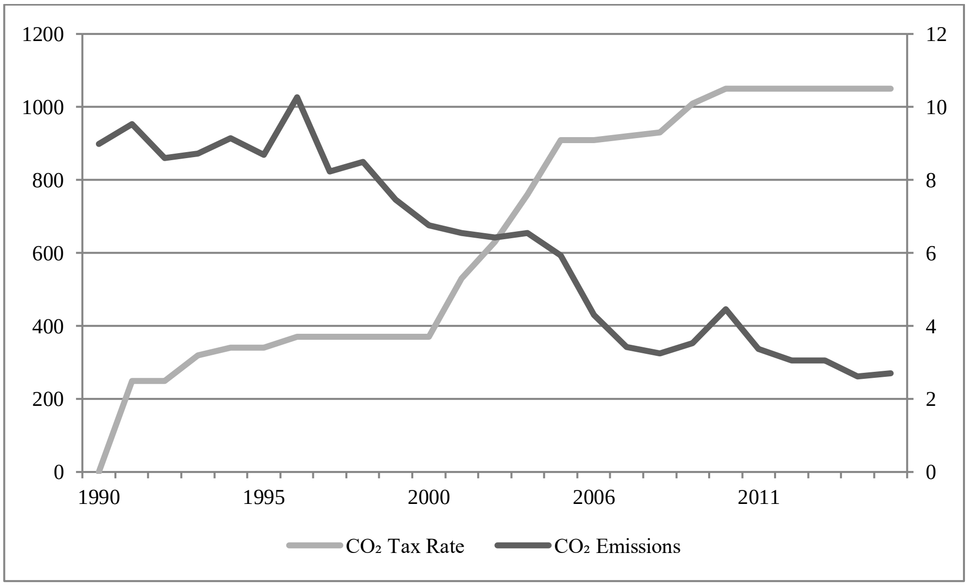
Source: own elaboration; data based on data by World Bank (2019)

The tax was initially set at 26 Euros (converted) per ton of emitted CO_2 (1991) after which it has been gradually increased to 120 Euros in 2018 (see figure 2). The largest upwards adjustment took place between 2001 and 2004 from around 40 Euros up to around 100 Euros per ton of CO_2 (Sweden 2018).[1]

[1] All prices according to a conversion rate of SEK 9.61 per Euro.

Simultaneously, carbon emissions in the residential sector have gradually decreased over the past 20 years (figure 2), with the steepest decrease between 1999 and 2006. The tax only appplies to sectors that are not subject to the European Emission Trading Scheme (ETS) and there is a wide range of exemptions for the industrial sector. Energy consumers in the residential sector are subject to 100% of the tax, which makes it an ideal area for policy evaluation.

Figure 2. Development of CO_2 Emissions by Swedish Residential Buildings (in million tons of CO_2, right hand axis) and Development of Swedish Carbon Tax rate (in SEK/ton CO_2, left hand axis)



Sources: Odyssee-Mure Database; Hammar and Åkerfeldt 2012

To our knowledge, there are few evaluations of the Swedish carbon tax. Shmelev and Speck (2018) do not find a significant impact of the carbon tax on overall emissions but find other fuel specific taxes to be significantly effective. The authors, however, do not focus on residential buildings but on the industrial and transport sector instead, which are both subject to other taxes and a number of carbon tax exemptions. Another study examines the impact of energy related taxation on carbon emissions from the transportation sector by using Synthetic Control Methods (Andersson 2017). The author suggests that the taxes reduced annual emissions by 11%. Similarly, Lin and Li use differences-in-differences regressions in order to estimate the carbon tax impact in five northern European countries (Lin and Li 2011). They do not find an impact of carbon taxation on CO_2 emissions in Sweden. The authors speculate that the non-existent impact is due to a number of exemptions, targeting various sectors of the economy. As there are only few studies on the effectiveness of carbon taxation in general and fewer studies still on the Swedish taxation scheme in particular, we concentrate the effects the carbon tax had on the residential sector, which is subject to the full impact of the carbon tax and has not been examined in the literature.

We use European country-level panel data for the years 1990-2016 and apply Difference in Differences (DiD) and Synthetic Control Methods (SCM) in order to study the severe increase in Swedish carbon tax rates around the year 2001 on residential CO_2 emissions. The results provide evidence for a moderate to strong and robust negative causal effect of the carbon tax augmentation on residential carbon emissions, in the range between 200 and 800 kg of CO_2 per capita per year. Using different control groups comprised of various countries with different carbon taxes or no carbon tax at all, we find the scope of the carbon tax to be decisive for the tax's effectiveness – dosis facit effectum.

As the implementation of or the increase in the carbon tax is currently being widely debated at all political levels, and as the residential sector accounts for around 25% of European CO_2 emissions, the current study fills an important gap in the literature.

This paper is structured as follows: chapter two will give an overview over the methods and data used for this paper. Results are presented in chapter three and discussed in chapter four. We draw a conclusion in chapter five.

2. Data and Methods

2.1. Data

European country-level panel data is used. There are 17 countries of the European Union (namely Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Poland, Slovakia, Spain, Sweden and UK) as well as Norway and Switzerland. Other countries of the European Union could not be considered due to a lack of data. Furthermore our panel data set is limited to the years 1990-2016 due to data availability.[2]

Residential carbon emissions per capita by country and year serve as our main dependent variable. We control for the prices of electricity, gas and oil, in addition to GDP per capita and Heating Degree Days (HDD) as a measure of country and year specific climatic conditions. Table A1 in the appendix lists all variables and their sources. Table B1 displays descriptive statistics.

The main challenge of our data is posed by the fact that there is no clean pre-period without treatment. The carbon tax in Sweden exists since 1991 and has been repeatedly increased ever since. However, after slight increases before 1996, and a plateau between 1996 and 2000, the carbon tax was drastically increased within a three year period. We treat the period before 2001 as the pre-treatment period and the period after 2000 as the post-treatment period. As we implicitly disregard the existing low treatment intensity in the pre-period, we underestimate the overall tax effect because a proportion of the difference in carbon emissions between Sweden and other countries in the period 1991-2000 is likely due to the lower treatment intensity in the 1990s. However, our methods (erroneously) attribute the overall difference as an unexplained pre-treatment country fixed effect. Our results should therefore be regarded as lower bound estimates.

Comprehensive data on the carbon tax rates of all sample countries and years does not exist. However, the total tax per unit of oil can be used as a proxy indicator of the overall tax burden on fossil fuels in a country. Figure 3 plots the total tax per unit of oil in USD (PPP) for all countries over time. Besides Sweden, there are two other countries that exhibit very high levels of energy taxation and increases after the year 2000, namely Denmark, Italy, Greece and the Netherlands. We will therefore employ additional specifications in our analysis below, where we omit these countries from the sample. Similarly, the countries that have implemented a carbon tax higher than 20 Euros per ton of CO_2 will be omitted from the control group in some specifications. In one of the SCM samples however, the control group consists of other countries that have some form of carbon tax in order to examine whether the higher Swedish tax has an impact on emissions vis-à-vis these lower intensity treatments.

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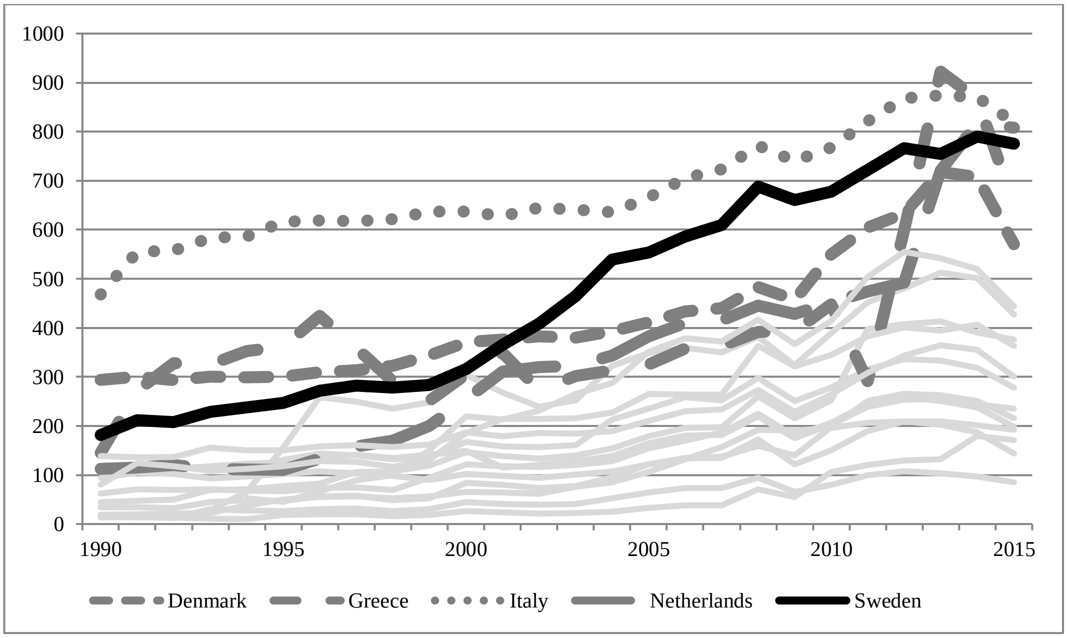
[2] Information on data sources, variables, variable names and units used see table A1 and B1 in the appendix

Figure 3. Total Tax per 1000 liters of oil (in USD/unit using PPP per 1000 liter light fuel oil)



2.2. Difference-in-Differences Regression

First, we perform a Difference-in-Differences Regression (DiD) in which residential CO_2 emissions (in tons of CO_2, by country and year) serve as the dependent variable. We include a dummy variable (dB) which equals 1 if the country is Sweden and 0 in the case of the control group. The time dummy variable equals 1 in the post-treatment period and 0 in the pre-treatment period. Instead of using a single pre- and post-period, we interact the treatment group dummy variable (dB) with an annual dummy. In addition, vector X contains further control variables, namely Heating Degree Days, GDP per capita as well as GDP per capita squared. The model takes the following form:

$$\frac{CO_2}{capita_{it}} = \alpha + \beta_1 dB_t + \beta_2 dT_i + \beta_3 dB_t * dT_i + \sigma \bar{X}_{it} + \varepsilon_{it}$$

Where

$$\widehat{\beta_3} = [E(CO_2/capita \mid dB=1, dT=0) - E(CO_2/capita \mid dB=0, dT=0)] - [E(CO_2/capita \mid dB=1, dT=1) - E(CO_2/capita \mid dB=0, dT=1)]$$

β1 Captures the differences between the treatment and control groups prior to the policy, whereas β2 captures the factors that would change per capita CO_2 emissions even in the absence of the policy intervention. Finally, β3 captures the difference between the changes after treatment in the treatment group and the changes in the control group. Thus, it measures the effect of the policy intervention.

We use several different sub-samples. First, the overall sample of all European countries is used, except Luxembourg for which we do not have sufficient data. Thus, the first sample containing all countries will underestimate the true effect since some control group countries also received treatment, albeit on a much lower scale. Secondly, we drop countries that showed exceptionally high energy taxes after the year 2000 (Italy, Denmark, the Netherlands and Greece) from the sample (sample 2). Finally, we drop all countries from the sample which have a carbon tax of more than 20 Euros per ton (Switzerland, Finland, Norway, UK and Ireland and the four countries with exceptionally high energy taxes in order to get a control group which is not tainted by treatment.

DiD-methods can only be used if treatment and comparison groups would have developed equally without the treatment. The DiD results can only be interpreted as causal if the parallel regression assumption is valid and if there are no confounding factors which selectively affected the treatment or control group after the year in which treatment begins. We can check the parallel regression assumption by plotting the development of CO_2/capita for the treatment and the control group over time. In addition, none of the yearly interaction terms before treatment should be significant in order to infer a causal relationship. Of course, the parallel regression assumption is already jeopardized by the fact that there have been frequent tax increases in Sweden during the 1990s. As this renders clean identification of the treatment effect impossible, we expect that in the pre-treatment years, some interaction terms coefficients may be significant but with a low negative effect. The effects after the intervention year should, in comparison, be highly significant and show much stronger effects.

2.3. Synthetic Control Model

In order to measure the effects the carbon tax increase on residential carbon emissions, we would need to know how the carbon emissions of the Swedish residential sector would have developed in the absence of the carbon tax increase. We therefore employ Synthetic Control Methods as a useful complement to the DiD, which can be criticized for its ambiguous selection of comparison units (Andersson 2017; Review and Jan 1990). SCM uses several donor countries as comparison units and constructs a synthetic control group out of a weighted average of these donor pool countries (on SCM estimation see Abadie, Diamond, and Hainmueller 2015; Abadie and Hainmueller 2014; Abadie, Diamond, and Hainmueller 2010). That means in order to estimate the effect of the carbon tax increase in Sweden, we need a synthetic Swedish residential sector as a control group which closely tracks the Swedish residential sector carbon emissions prior to the tax increase, which then serves as the unobserved counterfactual. While the parallel regression assumption in the DiD regression model is likely violated from the outset, the SCM suffers less from the fact that low intensity treatment existed in Sweden before 2001. SCM factors in these differences when generating a control group that matches the development of the Swedish residential CO_2 emission per capita in the pre-treatment period.

As in the DiD approach we use data on residential CO_2 emissions per capita for 19 European countries for the time period 1990-2016. As explanatory variables, country and year specific prices on oil and electricity, GDP per capita as well as HDD (in order to control for weather fluctuations) are included. We do not use prices for gas, district heating and biomass due to missing date for certain countries and years. Furthermore, we use different lags of our dependent variable.

There are three samples, and for each sample 6 specifications. Sample 1 includes all countries (except for Luxembourg due to a lack of data). Sample 2 includes all countries without carbon tax or with a carbon tax lower than 20 Euros. Besides this, countries with relatively high overall energy taxes after the year 2000 (see figure 3, Italy, Greece, Netherlands) are dropped. Sample 3 includes all countries with a carbon tax higher than 20 Euros (Switzerland, Finland, Norway, Denmark, UK, and Ireland). By using sample 3, we therefore compare low level treatment intensity countries (in the donor pool) with a high level treatment country (Sweden). We expect that in specification 1 and 3, the difference between the synthetic Sweden and real Sweden is smaller because countries in the donor pool are also experiencing low level treatment intensities, thereby underestimating the true reform effect. The difference between groups should be higher in the case in which we use countries without carbon taxation in the control group.

Table 1. Samples SCM

Sample 1 All countries	**Sample 2** No / low carbon tax countries	**Sample 3** Carbon tax countries
All countries included	Countries without carbon tax or with low carbon tax (less than 20 Euros per ton of CO_2), countries with exceptionally high energy tax are dropped	All countries with a carbon tax higher than 20 Euros
Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Poland, Slovakia, Spain, Sweden, Switzerland, UK	Austria, Belgium, Czech Republic, France, Germany, Poland, Slovakia, Spain, Sweden	Denmark, Finland, Ireland, Norway, Sweden, Switzerland, UK

For each sample, we run several specifications. In specification 1 we use three lags of CO_2 emissions (1990, 1994, and 2000). In specification 2 we use the years 1996, 1997, 1998, 1999, and 2000 as lags. Finally, we include all lags in specification 3. Specification 4 does not include lags but adds HDD and GDPpC as control variables, after which oil prices and electricity prices are added in specification 5. The final specification combines three lags with all controls (combined specification). In order to determine which specification is 'best' we compare the root mean squared prediction error (RMSPE) in order to evaluate which specification has achieved a minimization of the pre-treatment gap between treatment group and and synthetic control group. A list of variables used for each specification and the corresponding RMSPE values can be found in table 2.

Table 2. Specifications SCM

	Specification 1	Specification 2	Specification 3	Specification 4	Specification 5	Specification 6
Lags	1990, 1994, 2000	1996, 1997, 1998, 1999, 2000	All lags	No lags	No lags	1990, 1994, 2000
HDD				Yes	Yes	Yes
GDPpC				Yes	Yes	Yes
Price oil					Yes	Yes
Price electricity					Yes	Yes
RMSPE	0.05	0.04	0.03	0.97	0.06	0.03

In order to select predictor weights, we use a fully nested optimization method which yields more precise estimates according to Mcclelland and Gault (2017).

The model takes the following form:

$$\sum_{m=1}^{k} v_m \left(X_{1m} - X_{0m}W\right)^2$$

Vector X1 represents the characteristics of the treated unit, namely the Swedish residential sector, in the period before the treatment, k m represents the respective comparison country. Vector X0 captures the characteristics of the comparison units which are multiplied by the vector of weights (W) of the control countries. Thus, $(X_{1m} - X_{0m}W)$ captures the difference between the treated unit and the comparison units. v_m is the weight for each comparison country. In the case of the synthetic control W*, v_m is chosen such that the difference $(X_{1m} - X_{0m}W)$ is minimized meaning that it best resembles the original Swedish residential sector before the year 2001.

3. Results

3.1. Differences-in-Differences Regression

Table 3 displays the results of the three DiD specifications. In all three regressions, there is a strong suggestion of a negative relationship between carbon taxation and carbon emissions. The interaction terms of the Sweden dummy variable and the year dummy is insignificant before the year 2001, except in 1997, in which case the effect size is small (84 to 112 kg of CO_2 per capita), and in specification (2) for the year 1995. After the year 2000, the interaction terms are generally significant and effect sizes are negative and sizable, ranging from reductions of 200 kg to 525 kg per capita and year. Effect sizes become generally larger over time, although one must be careful when interpreting coefficients in later years. The farther we move away from the initial treatment date the more likely it is that confounding factors exert an influence. In specification (1) and (2) the coefficients of the interaction terms are negative and significant for six out of six post-treatment years. In specification (3), five out of six post-treatment interaction term coefficients are significant and negative, the other one being negative, and almost but not quite significant at the 10% level.

Summarizing, we can say that suggestive evidence exists that points toward a possible causal relationship between taxation and emissions in the residential sector. However, the parallel trends assumption is not completely fulfilled. Moreover, since we are working with country level data, there are a number of possible confounding factors, which could have selectively affected the carbon emissions per capita in Sweden or the control group in the post-treatment period.

Table 3. Difference-in-Differences Regression

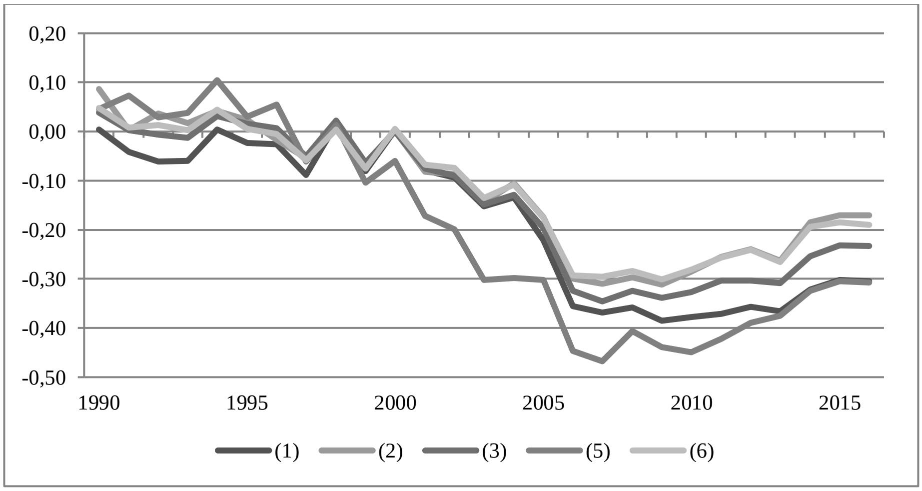
	(1) *All countries*	(2) *High tax countries dropped*	(3) *Only non-tax countries*
treatment*1995	-0.0359	-0.0825***	-0.0448
treatment*1996	-0.0084	-0.0011	0.0193
treatment*1997	-0.0844**	-0.1118***	-0.1039**
treatment*1998	0.0154	0.0008	-0.0240
treatment*1999	-0.0348	-0.0444	-0.0932
treatment*2000	0.0225	0.0272	-0.0868
treatment*2001	-0.2128**	-0.2229***	-0.3341**
treatment*2002	-0.2043**	-0.2123***	-0.3348**
treatment*2003	-0.2404**	-0.2365**	-0.3314*
treatment*2004	-0.2295*	-0.2124*	-0.3513
treatment*2005	-0.2885**	-0.2741***	-0.4440*
treatment*2006	-0.3606***	-0.3355***	-0.4723**
treatment*2007	-0.3723***	-0.3625***	-0.5251**
treatment*2008	-0.2894*	-0.2687**	-0.4721*
treatment*2009	-0.2996**	-0.2834***	-0.4841**
HDD	0.0003	0.0003***	0.0003
GDP per capita	0.0000	0.0000	0.0001
GDP per capita squared	0.0000	0.0000	0.0000
Constant	0.7213	0.7086	0.2493
Additional control			
Year dummy variables	yes	yes	yes
Sweden dummy variable	yes	yes	yes
Observations	286	224	175
r2			

p-values indicated as stars: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.2. Synthetic Control Method

Figure 4 plots the differences between Sweden and its synthetic counterpart for sample 1 (all countries) and for five out of six specifications (as described in the methods section) for which RMSPE values are small and quite similar (0.05; 0.04; 0.03; 0.06; 0.04). Specification (4) is not reported as it exhibits a much higher RMSPE (0.97) and its pre-treatment development was very different from the one in Sweden. The five specifications in which the minimization of pre-treatment differences of the outcome variable was successful provide strong evidence for a negative causal relationship of carbon taxation and residential carbon emissions. The effect sizes range from 200 to 450 kg of carbon emissions per year. After the year 2012, we see that the gap between Sweden and synthetic Sweden shrinks. We interpret this development as further evidence in favor of the hypothesized relationship between taxation and emission. Many countries have only recently begun to introduce carbon taxation, such as France (2014), Switzerland (2008), the UK (2013) and Ireland (2010) and thereby decreased the difference in the treatment intensity between Sweden and all other countries. The country weights chosen to construct the synthetic residential sector consist mainly of Norway (around 65%) and to a smaller part of Denmark (~13%). Furthermore, Switzerland (12%) is used in specification 6, France (16%) in specification 2, Poland (18%) in specification 1 and Finland (18%) in specification 5. A detailed list of all country weights can be found in the appendix C1.

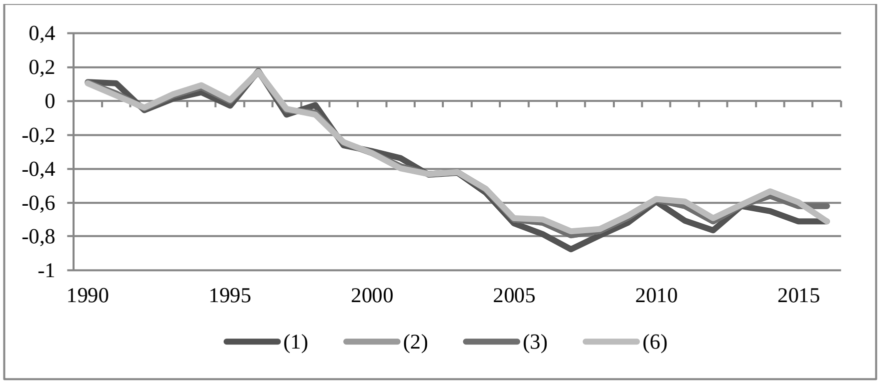
Figure 4. Synthetic Control Method (sample 1, all countries)



Notes: The lines display the difference in the dependent variable (residential CO_2/ capita per country and year) between Sweden and its synthetically generated counterpart. The five different lines represent five different model specifications (as summarized in table 2).

Figure 5 plots the differences between Sweden and its synthetic counterpart for sample 2 (only countries with low carbon taxes and without high overall energy taxation.). Four out of six specifications for which RMSPE values are small and quite similar are plotted, where specifications (2) and (3) are almost identical. The two specifications containing control variables only do not minimize pre-treatment differences in the outcome variables and are omitted from the graph. Again the graph provides evidence for a treatment effect after the year 2000. As we have dropped countries that have either imposed carbon taxes or high energy taxation levels, we expect the treatment effect to be stronger using this sample. Indeed, the peak treatment effect is close to 800 kg of carbon dioxide emissions per year (for the years 2005, 2006, and 2007). In the creation of a synthetic Sweden, France and Spain serve as primary input countries. Poland plays a subordinated role in specifications 1, 2 and 3. A detailed list of all country weights can be found in the appendix C2.

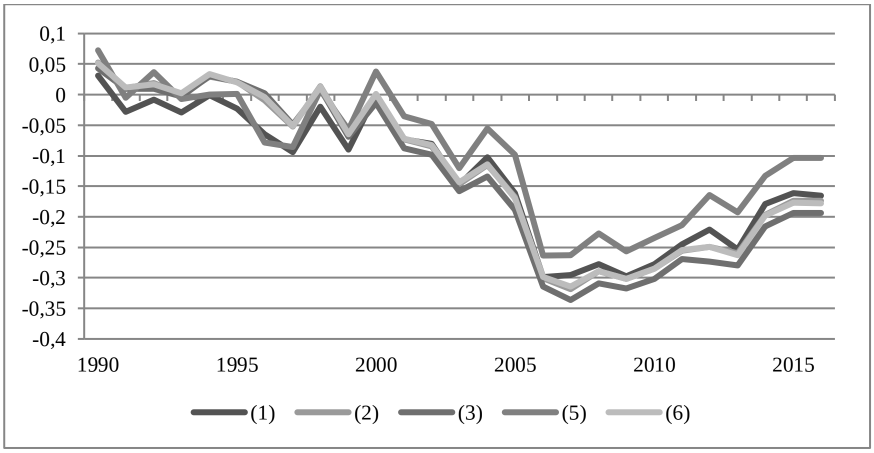
Figure 5. Synthetic Control Method (sample 2, countries with not carbon tax or carbon tax lower than 20 Euros and no major tax increases)



Notes: The lines display the difference in the dependent variable (residential CO_2/ capita per country and year) between Sweden and its synthetically generated counterpart. The four different lines represent four different model specifications (as summarized in table 2).

Finally, the SCM results for sample 3 consisting of countries already imposing a carbon tax higher than 20 Euros per ton of CO_2, are plotted in figure 6. Again, the impact of the relatively high tax increase in Sweden after the year 2000 affects carbon dioxide emissions negatively. We only include countries with (lower intensity) carbon taxation schemes and the effect sizes are therefore underestimated because only the difference in carbon taxation between Sweden and donor countries is being considered as treatment. Effect sizes range from 200 to 300 kg of carbon emissions per capita and year (for the years 2005 to 2010) after which the effect sizes start shrinking. As we have stated above, this is caused by donor pool countries imposing new carbon taxation schemes or increasing taxation rates. In this sample Norway makes up the greatest part of the synthetic control (around 71%) followed by Denmark (~20%). A detailed list of all country weights can be found in the appendix C3.

Figure 6. Synthetic Control Method (sample 3)

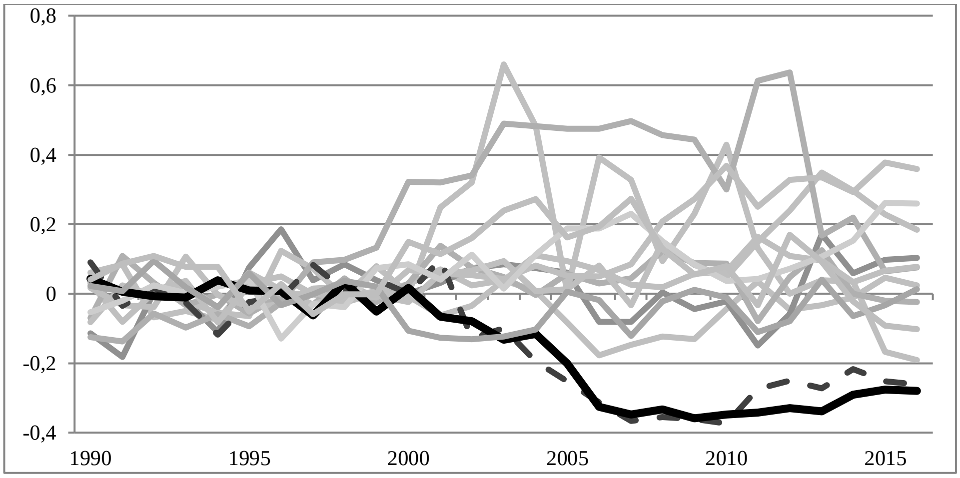


Notes: The lines display the difference in the dependent variable (residential CO_2/ capita per country and year) between Sweden and its synthetically generated counterpart. The five different lines represent five different model specifications (as summarized in table 2).

Robustness Tests

In order to test for the robustness of the results presented above we ran several placebo tests for each sample. Figure 7 plots the results of a placebo test for sample 1 based on sample specification 6. Each line represents a separate Synthetic Control Model. We cycle through the list of all sample countries, pretending each to be the treatment country. Figure 7 plots the resulting differences in the outcome variable between each treatment country and its synthetic counterpart. We omit countries for which the minimization of pre-treatment differences did not work - in this case Norway. There are only two countries for which a considerable treatment effect can be found – Sweden (solid black line) and Slovakia (dashed line).

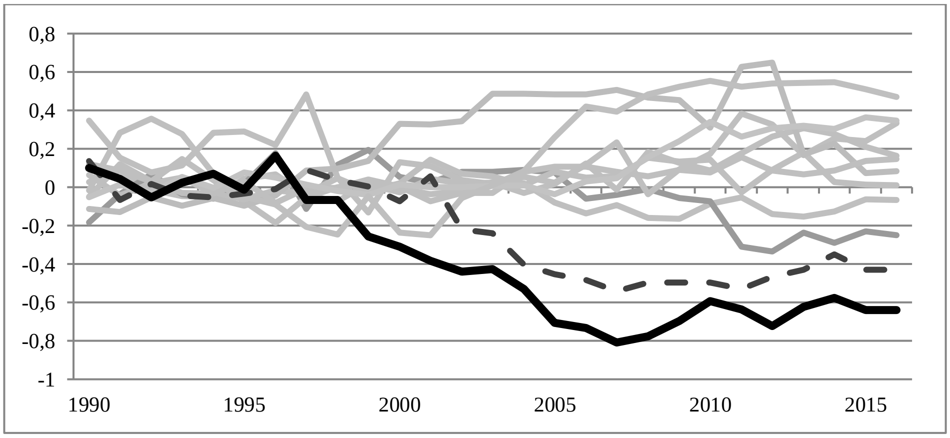
Figure 7. Placebo Test (sample 1, all countries)



Notes: Each placebo tests (each line) treats one country as the treatment country, regardless of whether treatment was actually received or not. Each line displays the difference in the dependent variable (residential CO_2/ capita per country and year) between the treatment country and its synthetically generated control group. Sweden is represented by the solid black line. The dashed line represents Slovakia.

Figure 8 plots the placebo tests for sample 2. Again, apart from Sweden, only Slovakia seems to have undergone some form of treatment around the year 2001. Spain had to be omitted from the graph because its pre-treatment RMSPE value is much higher than for all other countries.

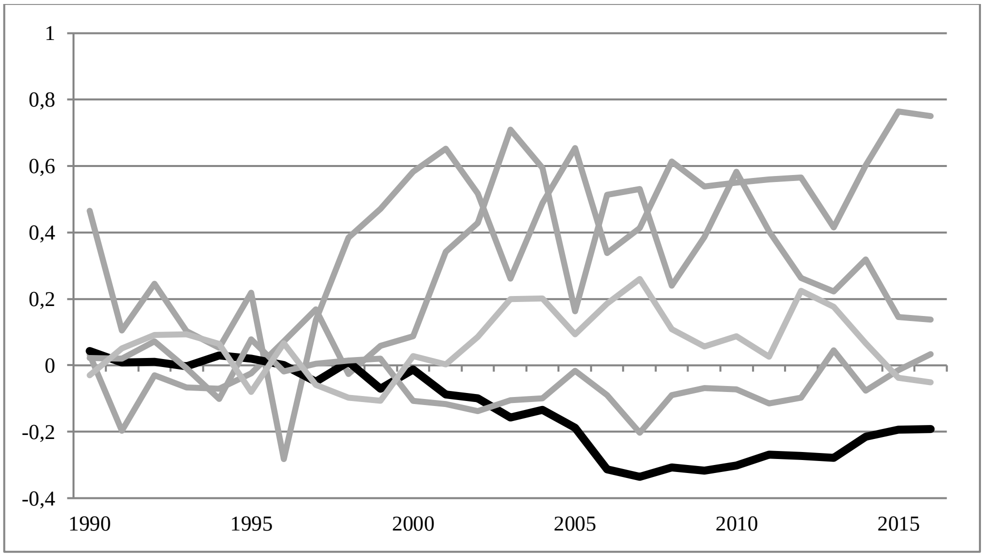
Figure 8. Placebo Test (sample 2, countries with no or low carbon tax and low energy tax)



Notes: Each placebo tests (each line) treats one country as the treatment country, regardless of whether treatment was actually received or not. Each line displays the difference in the dependent variable (residential CO_2/ capita per country and year) between the treatment country and its synthetically generated control group. Sweden is represented by the solid black line. The dashed line represents Slovakia.

The placebo tests for sample 3 (figure 9) show that the country with the strongest effect size is indeed, Sweden (solid black line). There are only few lines here because the number of countries with carbon taxation is small. Denmark was dropped as the pre-treatment minimization of carbon emission levels was not successful.

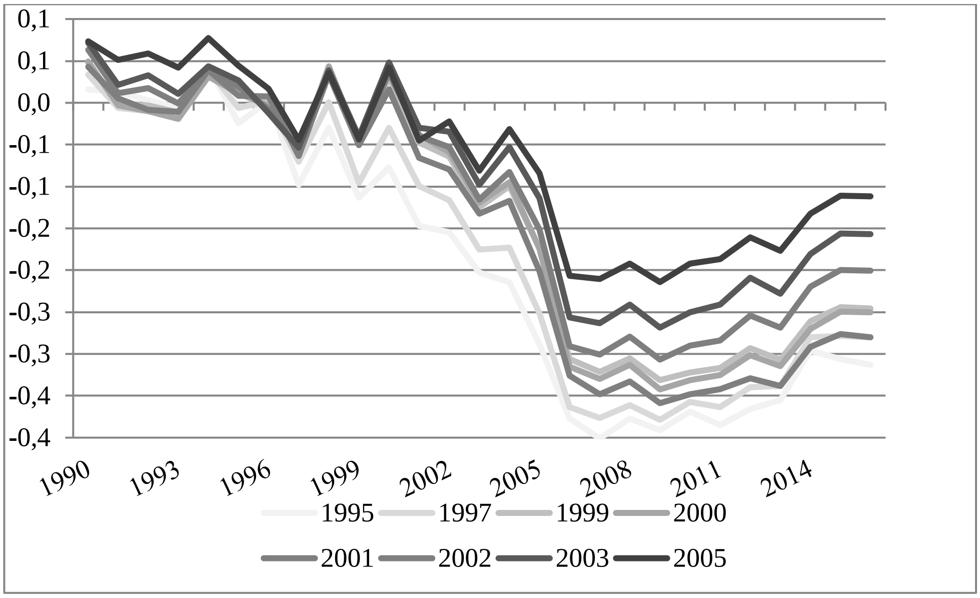
Figure 9. Placebo Test (sample 3, carbon tax countries)



Notes: Each placebo tests (each line) treats one country as the treatment country, regardless of whether treatment was actually received or not. Each line displays the difference in the dependent variable (residential CO_2/ capita per country and year) between the treatment country and its synthetically generated control group. Sweden is represented by the solid black line. The dashed line represents Denmark.

We furthermore ran in-time placebo tests for which we use specification 6 (all control variables and lags for the years 1990, 1994, and 2000). Each line represents a separate Synthetic Control Model each one using another year between 1995 and 2005 as the treatment year. We run these placebo test for sample 1 (figure 10), sample 2 (figure 11) and sample 3 (figure 12). As figure 10 shows, no matter which year is defined as the treatment year, differences in carbon emissions only start to decrease around the year 2001 with the major decrease happening between the years 2005 and 2007. The models using earlier years as the treatment year show slightly stronger effects since they capture the low treatment intensity effects of the earlier carbon tax scheme.

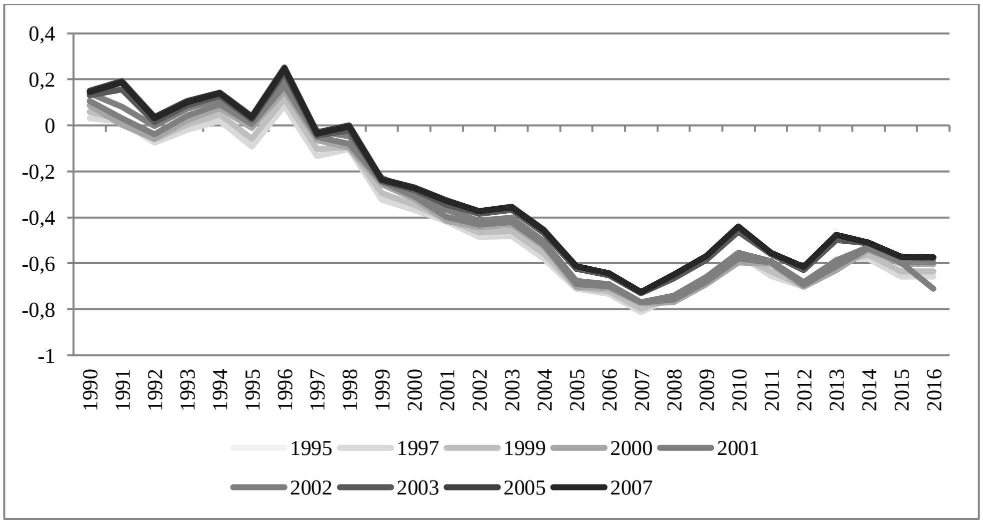
Figure 10. In Time Placebo Test (sample 1)



Notes: Each placebo tests (each line) treats one year as the beginning of treatment, regardless of whether treatment was actually received or not. Each line displays the difference in the dependent variable (residential CO_2/ capita per country and year) between the treatment country (Sweden) and its synthetically generated control group.

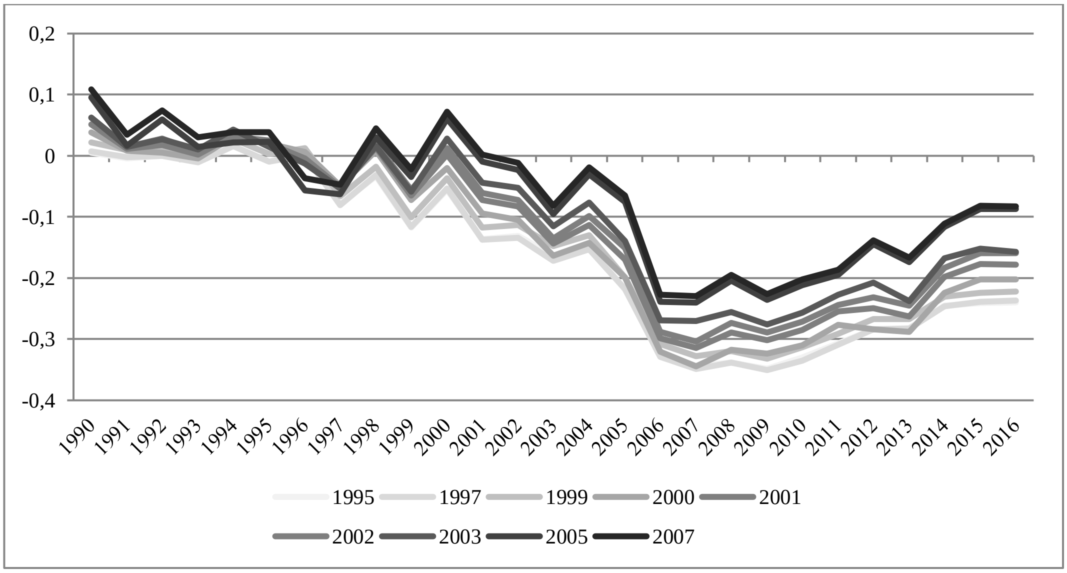
The results of the in time placebos for sample 2 show hardly any differences between the different treatment years. However, in comparison to sample 1 the treatment already shows partial effects starting in the year 1998. This could be due to anticipation effects. Major reduction in CO_2 emissions were achieved in the time frame between 1998 and 2007.

Figure 11. In Time Placebo Test (sample 2)



The results of the in time placebo tests for sample 3 show equally similar results to the results of sample 1. The reduction in carbon emissions starts around the year 2001 and experiences the steepest decrease between 2004 and 2006.

Figure 12. In Time Placebos (sample 3)



Summarizing this section we conclude that the SCM results show strong and robust negative effects of Swedish carbon taxation on residential carbon emissions.

4. Discussion

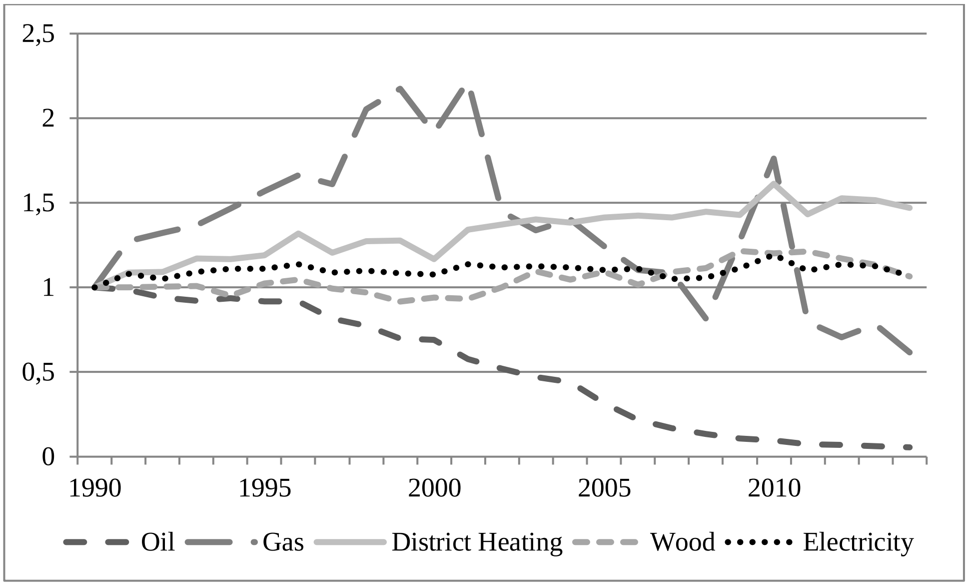
The results of this study show strong and robust negative effects of the Swedish carbon tax increase in the early 2000s on residential carbon emissions. The results suggest that per capita carbon emissions are reduced by between 200 and 800 kg per year. As some of our lower bound estimates are most likely underestimating the true effect, the effect size must be regarded as high, given that average yearly residential per capita carbon emissions are close to 1.75 tons of CO_2 (authors own calculation based on data by Odyssee Mure).

The results therefore suggest the carbon tax to be an effective instrument in reducing residential carbon emissions. However, this study also showed that the scope of the carbon tax determines its effect size. The strong reductions of residential carbon emissions were mainly driven by the carbon tax increase in the early 2000s. Comparing the development of Swedish residential CO_2 emissions with a weighted combination of countries with a carbon tax between 20 and 80 Euros we still find considerable reductions of residential carbon emissions by around 250-350 kg of CO_2.

The statistical results in previous sections of this paper play out on the macro level. It is, however, desirable to examine the micro-level actions that bring about these carbon emission reductions. The remainder of this section presents secondary evidence that corroborates the empirical results above.

Figure 13 displays the consumption of energy carriers in Sweden after the year 1990 (the year 1990 being the index year). One can see that oil consumption exhibits a strongly decreasing trend. However, the main decrease of oil consumption happened between the years 2000 and 2007, right after the carbon tax increase. At the same time electricity, district heating and wood consumption increased slightly after the year 2000. Gas consumption increased before the 2000s and decreased afterwards which could be interpreted as consumers initially switching from oil to gas, and, after the large upwards adjustment of the carbon tax, they started transitioning to electricity, district heating or wood instead.

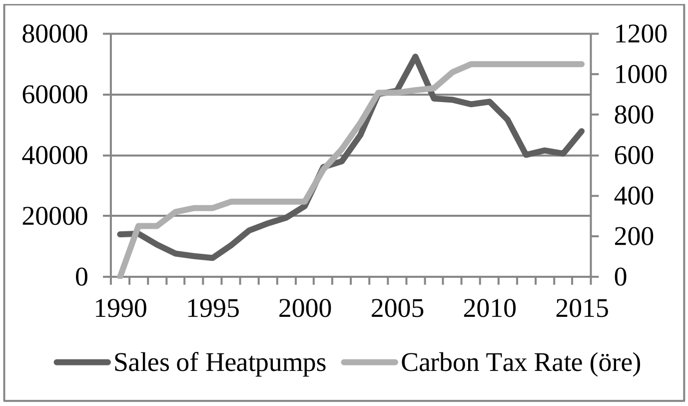
Figure 13. Development of energy consumption by energy carrier



Source: own elaboration based on data by (Odyssee-Mure)

One way of increasing energy efficiency and thus, mitigating residential carbon emissions is the use of heatpumps. Figure 14 shows the development of the sales of heatpumps in Sweden. Between 1990 and 2000 annual sales of heatpumps hovered around 18,000 and 23,000. One can see that with the strong augmentation of the carbon tax in the early 2000s, the sales of heatpumps skyrocketed from 25,000 to 60,000, which suggests that private households responded quickly to the increasing energy costs by switching to low-carbon technologies.

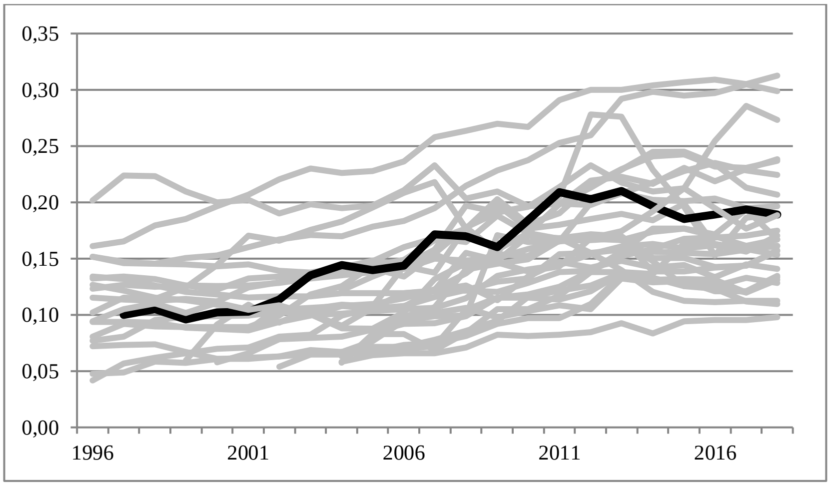
Figure 14. Annual Sales of Heatpumps (left hand axis) and Swedish Carbon Tax Rate per tonne of CO_2 (right hand axis)



Source: Svenska Kyl & Värmepump Föreningen; (Hammar and Åkerfeldt 2012)

One might argue that Swedish households were particularly well suited to switching to low-carbon technologies because of relatively inexpensive nuclear powered electricity generation. However, as figure 15 shows, Swedish electricity prices -even when considering purchasing power parities- have never been below the European average for the whole time-period after 2001. Hence, low electricity prices do not seem to be a prerequisite for a successful low-carbon technology transition given a high carbon tax.

Figure 15. Electricity Prices by country and year



Source: own elaboration, based on data by the OECD
Notes: Prices (including taxes and levies) in Euro (PPP) per Kilowatt-hour

A high carbon tax leads, of course, to welfare losses in the short-run. Due to the rapid adaption to the price signal and the corresponding transition to low-carbon-technologies, it can be argued that it enhances overall welfare from an intergenerational perspective by internalizing negative external effects.

5. Conclusion

We study the impact of Swedish carbon taxation on carbon emissions in the residential sector. Using macro level data on residential carbon emissions, we firstly estimate Difference-in-Difference regressions, treating the Swedish increase in carbon taxation after the year 2000 as a quasi-experimental intervention. While the DiD-results support our hypothesis of a negative impact of carbon taxation on carbon emissions in the residential sector, the DiD-evidence must be seen as suggestive rather than strictly causal. The Swedish carbon tax has been introduced in 1991 and was steadily and slightly increased throughout the 1990s, until the major upward shift occurred after 2001, thereby jeopardizing a clean distinction between a pre- and post-treatment period.

In order to overcome the shortcomings of the DiD approach, we secondly perform a synthetic control analysis. A weighted combination of donor countries serves as a synthetic Sweden that serves as the counterfactual. We find evidence for a causal impact of the tax increase and lower emissions in the residential sector. Using various sets of control group countries, we estimate a large effect size when comparing Sweden with countries that have not implemented a carbon taxation scheme, i.e. a reduction of residential carbon emissions per capita and year by 800 kg. When comparing Sweden, with its high carbon tax level, to countries that have implemented lower carbon taxation levels, we still find a moderate reduction of around 300 kg per capita per year. In-time placebo tests as well as country placebo tests suggest that these results are robust.

We finally present a number of descriptive Swedish time series statistics on fuel-type consumption and sales of low-carbon heating systems that corroborate our hypothesis. The timing of oil-substitution as well as the increase in heat-pump-sales coincides with the carbon tax increase after the year 2000. We also rule out the possibility of inexpensive nuclear powered electricity generation as a prerequisite for a low-carbon-technology transition as Sweden does not display particularly low electricity prices when compared to other countries.

Our results suggest that carbon taxation can be an effective policy tool in lowering emissions in the residential sector if taxation levels exceed 120 Euros per ton of CO_2 as it is the case in Sweden. Since there also strong theoretic reasons in favour of its efficiency vis-à-vis alternative climate policies (command and control methods), which generally exhibit higher bureaucratic costs, carbon taxation may become a more attractive policy tool in the future.

Our research is limited by the fact, that we do not fully investigate differing treatment intensity levels, i.e. heterogeneous tax rates, as there currently exists no information on carbon taxation rates for multiple countries over time. Instead, we used the substantial increase in the Swedish carbon tax as a binary treatment variable. Future research may want to concentrate on generating and exploiting a richer data set on taxation levels in order to yield more nuanced results.

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7. Appendix

A Data Sources

Table A 1. Data Description

Variable	Name	Unit	Source
Poil	Price on oil	USD per 1000 litres of light fuel oil	OECD
Pgas	Price on gas	USD per MWh natural gas	OECD
Pelec	Price on electricity	USD per MWh electricity	OECD
GDP	GDP	Million Euros (2010)	Odyssee-Mure
GDPpC	GDP per capita [GDP / Population]		Odyssee-Mure
Population	Population	thousand inhabitants	Odyssee-Mure
CO2E	CO_2 Emissions in the residential sector	Million tons of CO_2	Odyssee-Mure
CO2EpCalt	CO_2 Emissions per capita mt	Million tons of CO_2	Odyssee-Mure
CO2EpC	CO_2 Emissions per capita	Tons of CO_2	Odyssee-Mure
HDD	Heating Degree Days	Days	Odyssee-Mure

B. Descriptive Statistics

Table B 1. Descriptive Statistics of Data Set

Variable	Obs	Mean	Std. Dev.	Min	Max
Year	513	2003	7.80	1990	2016
Toil	511	255.68	221.82	6	1055
Poil	512	717.03	440.44	43.12	2091
Pelec	512	166.47	74.82	10.3	409.19
GDP	491	621,840.90	699,063.4	24241.72	2855352
GDPpC	491	31,031.74	16,332.09	4,124.95	83,857.27
GDPpC2 (x 1 Mio)	491	1230	1330	17	7030
CO2E	503	730.77	2902.18	0.64	14,783
CO2EpC	503	1.76	0.75	0.13	3.73
Population (x 1 Mio)	513	23.2	24.7	3.8	82.5
HDD	513	2885.92	8405898	7772633	4947

C. Additional Results

Table C 1. Weighted Combinations of Synthetic Sweden (sample1)

Country	Specification 1	Specification 2	Specification 3	Specification 4	Specification 5	Specification 6
Austria	0.002	0	0	0.037	0	0.008
Belgium	0	0	0	0.027	0	0
Czech Republic	0	0	0	0.063	0	0
Denmark	0.13	0.198	0.141	0.036	0.055	0.168
Finland	0.001	0	0	0.343	0.179	0
France	0.001	0.16	0	0.027	0	0
Germany	0.001	0	0	0.05	0	0
Greece	0	0	0	0.027	0	0
Ireland	0	0	0	0.028	0	0
Italy	0.002	0	0	0.027	0.229	0.034
Netherlands	0	0.009	0	0.035	0	0
Norway	0.657	0.632	0.708	0.035	0.537	0.675
Poland	0.178	0	0.065	0.092	0	0
Slovakia	0.022	0	0	0.062	0	0
Spain	0	0	0	0.028	0	0
Switzerland	0.003	0	0	0.045	0	0.115
UK	0.001	0	0.086	0.039	0	0
RMSPE	0.0502	0.0409	0.0304	0.9676	0.0625	0.0353

Table C 2. Weighted Combinations of Synthetic Sweden (sample 2)

Country	Specification 1	Specification 2	Specification 3	Specification 4	Specification 5	Specification 6
Austria	0	0	0	0.067	1	0
Belgium	0	0	0	0.016	0	0
Czech Republic	0	0	0	0.056	0	0
France	0	0.385	0.385	0.018	0	0.491
Germany	0	0	0	0.727	0	0
Poland	0.135	0.03	0.03	0.057	0	0
Slovakia	0	0	0	0.047	0	0
Spain	0.865	0.585	0.585	0.012	0	0.509
RMSPE	0.1428	0.1401	0.1401	1.5560	0.7378	0.1403

Table C 3. Weighted Combinations of Synthetic Sweden (sample 3)

Country	Specification 1	Specification 2	Specification 3	Specification 4	Specification 5	Specification 6
Denmark	0.206	0.174	0.155	0	0.254	0.169
Finland	0	0	0	0.339	0.006	0
Italy	0	0	0	0	0.007	0
Norway	0.69	0.726	0.722	0	0.734	0.719
Switzerland	0.104	0	0	0	0	0.026
UK	0	0.1	0.123	0.661	0	0.086
RMSPE	0.0472	0.0324	0.0316	1.2937	0.0474	0.0324