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Residential CO₂ Emissions in Europe and Carbon Taxation: a Country-Level Assessment

Dorothee Charlier*, Mouez Fodha[†], Djamel Kirat[‡]

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Abstract

This paper examines the determinants of residential CO₂ emissions, which are not covered by the European Union Emissions Trading System (EU ETS), in 19 European countries between 2000-2017. Using both static and dynamic panel models, we found strong relationships between CO₂ emissions per capita, GDP per capita, energy prices and heating needs. We then assessed the impact of European carbon taxation and show that a €20/tonne CO₂ tax lowers emissions by 1% on average. We found that this tax affects countries differently in terms of tax revenue-to-GDP ratio. Poland and the Czech Republic would have to pay the highest contribution, and Portugal and Denmark the lowest. Finally, we propose a scenario that equalizes countries' tax burdens. We show that, were Europe to redistribute all tax revenues, the main beneficiaries would be Poland and Belgium, while Denmark and Luxembourg would have to pay a surtax.

Keywords: CO₂ emissions; Residential Sector; Panel data; Energy prices; Carbon tax.

JEL classification: Q48, Q52, C33.

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1 Introduction

According to the European Environment Agency (2020), EU greenhouse gas emissions decreased by 2% in 2018, but this promising trend is still insufficient, for at least two reasons. First, emissions covered by the European Union Emissions Trading Scheme (EU ETS) have effectively decreased, but those not covered by the EU ETS have not changed significantly. Secondly, the EU 2030 climate and energy framework sets a binding target to cut emissions by at least 40% below 1990 levels by 2030. The residential sector accounts for around 20% of European CO₂ emissions, with energy demand mainly driven by heating (Eurostat, 2019).¹ Because emissions from the residential sector cannot be displaced, climate policies could be effective but a clear understanding of their consequences is required.

The first objective of this paper is to study the determinants of residential CO₂ emissions in Europe. We used panel data for 19 European countries from 2000-2017 and reveal huge differences between countries' CO₂ emissions. We first estimated a static model that assumes an instantaneous adjustment of CO₂ emissions per capita to changes in energy prices, income and heating needs. We then extended this model to account for dynamic adjustments and computed short-term and long-term elasticities of per capita CO₂ emissions relative to each driver. Our results show strong relationships between CO₂ emissions per capita, GDP per capita, energy prices and heating needs. We found that the income elasticity of CO₂ emissions per capita is not constant and depends on the level of GDP per capita. When instantaneous adjustment is assumed, the elasticities of per capita CO₂ emissions relative to natural gas and heating-oil prices are found to be -0.23 and -0.14 respectively. The corresponding short-term elasticities from dynamic models are -0.12 and -0.11 , and the long-term elasticities estimated to be -0.47 and -0.38 . Our results are in line with those from studies analyzing the determinants of energy demand in the residential sector. Although these studies did not focus on CO₂ emissions, they report elasticities significantly positive and lower than one for income and negative for prices, with values between -1.7 and -0.04 . We also confirm that CO₂ emissions per capita increase with heating needs, the short-run elasticities fall between

¹Even though very hot summers were recorded for the years 2014 and 2015, there was evidence of significantly higher heat demand in the residential sector. There was a 3.4% increase in the number of heating degree days in the EU in 2015 compared with 2014 (European Environment Agency, 2017).

0.77 and 0.85, and the corresponding long-run elasticities are three times higher.

Our second objective is to examine whether the carbon tax can be an effective complement to the EU ETS for emissions that remain unregulated, like those from the residential sector. We measured the consequences of the tax on CO₂ emissions and how the burden of this tax is distributed among countries. Imposing a European carbon tax could increase the regressive properties of carbon taxation, which could result in a popular rejection of the policy.² Our econometric estimates were used to predict which countries would bear the largest increase in energy prices from a European carbon tax. We assumed a 100% pass-through rate of the tax into energy prices and assessed the short-term impacts of the tax policy. We confirmed that this tax leads to inequalities in the tax burden, as measured by the ratio of tax revenues to GDP by country. Our simulations show for example that a carbon tax of €20 per tonne represents 0.02% of Danish GDP but 0.17% of that of Poland in terms of tax revenue. These differences in the tax burden, highlighted in previous works (see Metcalf et al. (2008) or Hassett et al. (2009) for example), may be a limit to the effectiveness of the policy. For instance, Borozan (2019) found that the tax has little effect on the energy consumption of rich households, and redistribution targeted at poor households increases their consumption. He showed that the carbon tax policy may be ineffective or even counterproductive. Finally, we propose a policy that may correct for these inequalities. It consists of the redistribution of carbon tax revenues in order to obtain, ex-post, an equal tax-to-GDP ratio among all countries. We show that the main beneficiaries would be Poland, the Czech Republic and Belgium, while Denmark, Spain and Luxembourg would have to pay a surtax.

The remainder of the paper is structured as follows: Section 2 contains a brief literature review on energy demand drivers, CO₂ emissions and carbon taxation in the residential sector. Section 3 describes the data used. Section 4 presents the methodological approach and Section 5 the empirical findings. The simulation results of the carbon tax policy are contained in Section 6. Section 7 concludes, and additional materials are provided in the appendix.

²The acceptability issue in France has already been highlighted in Bureau (2012). One important illustration is the 2019 "GILETS JAUNES" protests in France that stopped the planned carbon tax increase. A detailed study of the determinants of the "GILETS JAUNES" movement, and its interaction with carbon taxation, can be found in Douenne and Fabre (2019) and (2020).

2 Literature review

The role of energy in the residential sector is an important concern for climate policy design, as this sector is often associated with issues such as energy taxation and prices as well as carbon mitigation and redistribution. We first analyze the determinants of CO₂ emissions in the residential sector and then estimate the consequences of carbon taxation in Europe. For consistency, we have divided the literature review into two parts. The first focuses on energy consumption and CO₂ emissions in the residential sector, while the second focuses on the distributional effects of carbon taxation.

2.1 Energy demand and residential CO₂ emissions

The literature mainly focuses on residential energy demand, and not specifically on CO₂ emissions. These two variables are closely linked since the energy mix is predominantly based on fossil fuels and the technologies have remained relatively stable over time (see Table 9 in the appendix). As noted by Kriström (2008), the key drivers of residential energy demand are (i) prices, (ii) income and (iii) weather conditions. This was confirmed by Du et al. (2021) who analyzed the energy demand in China's urban residential sector over the period 2001–2014.

First, regarding the role of prices, it is useful to distinguish the short-run from the long-run. Indeed, the demand for energy services is combined with demand for other goods such as capital goods (e.g., devices) to produce an energy service. In the short-run, capital is fixed, and energy demand is inelastic to prices. In the long-run, energy demand becomes more elastic because households can react to a price increase by purchasing more efficient appliances and equipment. Price elasticities vary over time, and by type of fuel and geography, and are always found to be negative, varying from -0.04 to -1.7 . Alberini and Filippini (2011) presented an empirical analysis of the residential demand for electricity using state-level annual aggregate data for 48 US States from 1995 to 2007. They obtain a long-run price elasticity of -0.70 . Filippini et al. (2014) focused on the EU-27 member states over the period 1996-2009. They estimated the price elasticities of residential energy use to be between -0.26 and -0.19 . Our results are clearly in line with these findings, even though

we consider CO₂ emissions and not energy demand per se. Our CO₂ emissions per capita elasticities relative to energy prices range from -0.25 to -0.1 in the short-run and -0.5 to -0.3 in the long-run.

Secondly, income also plays an important role in energy demand. Most studies conclude that income elasticity of energy demand is often lower than one, which is consistent with normal-good status even in a long-run perspective. Filippini et al. (2014) obtained an income elasticity of 0.42 for the EU-27 member states over the period 1996-2009. Auffhammer and Wolfram (2014) presented evidence suggesting that the shape of income distribution drives household acquisition of energy-using goods in China. As noted in the literature review by Miller and Alberini (2016) and the meta-analysis of 428 papers in Labandeira et al. (2017), growth in business activity is an important factor affecting energy consumption, particularly over long periods (IEA, 2018).

Third, weather conditions help explain changes in energy consumption: colder winters increase heating needs, and thus energy consumption (see Mansur et al., 2008; Honoré, 2018; Thomas and Rosenow, 2020).

Finally, following on from the role of energy prices, energy policies also explain energy demand. Thomas and Rosenow (2020) emphasized that European countries should implement more ambitious policies to improve heating efficiency.³ Thonipara et al. (2019) studied panel data from the 28 countries of the European Union and Norway over sixteen years and showed that carbon taxation represents an effective means to improve energy efficiency. They found that the carbon tax has two major effects, especially in Sweden: (1) a general reduction in energy consumption and (2) changes in the energy mix. However, a carbon tax of only €4.50 per tonne of CO₂ as in Latvia or €30 in Finland cannot achieve the far-reaching effects in energy efficiency as observed in Sweden (with a carbon tax of €120 per tonne of CO₂).

³Among the energy policies to be implemented, carbon taxation is a relevant tool but must be viewed with caution. Cansino et al. (2011) and Pablo-Romero et al. (2017) studied the residential energy consumption trends for the period 1993-2013 by main world regions and per capita gross national income levels. They both confirmed the need for the EU region to implement additional energy policies to accelerate energy transition.

2.2 Distributional effects and efficiency of carbon taxation

There is an extensive literature on the unequal geographic and social burden of carbon taxation (for the U.S. economy, see for example Hassett et al., 2009; Mathur and Morris, 2012; Rausch and Schwarz, 2016). Specifically, regarding the impact of energy taxes on residential energy consumption in the European Union, Borozan (2019) emphasizes two important issues: the heterogeneous consequences of the carbon tax between countries, and also the low efficiency of the tax on residential energy consumption. The author shows that higher energy taxes may increase energy consumption in lower energy-consuming countries. This counterintuitive result can be explained as follows: (1) carbon taxes alone have very little impact on energy consumption, and energy demand is even inelastic to price in the short-run; and (2) countries with low energy consumption have accompanied the increase in carbon taxes with a significant redistribution towards low income households, which may have contributed to increased energy consumption. Conversely, in high energy-consuming EU countries, an increase in the carbon tax leads to a very slight decrease in energy consumption. Borozan (2019) concluded that an energy tax is certainly not efficient on its own. Macaluso and White (2011) analyzed the energy and greenhouse gas emissions impacts of adding a carbon tax to efficiency improvement standards for the residential sector in Canada and the US. They showed that, compared to standards alone, the addition of the tax led to further residential emission reductions. Similarly, Giraudet et al. (2011) assessed the impacts of French policies for residential heating energy consumption and concluded that interactions among energy policy instruments are additive.

In the French case, Charlier et al. (2018) showed that implementing a carbon tax on a dwelling decreases energy consumption and greenhouse emissions by 1.05% and 3.25% respectively. They also pointed out that a carbon tax represents an additional burden for households living in poorly insulated dwellings and that such a policy should be considered carefully in terms of social justice. When designing a carbon tax, the impact on low-income households is certainly an issue; a common criticism of the carbon tax is that it disproportionately affects low-income households (Sumner et al., 2011). This last issue is important because even if climate policies are accepted, the regressivity of the carbon tax may be a potential source of opposition to energy policy. Indeed, the poorest households dispropor-

tionately have to pay for it. The "GILETS JAUNES" movement, which halted the planned implementation of the carbon tax, is an interesting example and has been the subject of detailed studies (Douenne (2020) and Douenne and Fabre (2019), (2020)). Douenne (2020) assessed the distributional impacts of the French carbon tax and showed that the policy is regressive but could be made progressive by redistributing the revenue through uniform lump-sum revenue recycling. However, it would still generate distributive effects and harm a considerable number of low-income households. Douenne and Fabre (2019) and (2020) highlighted ambiguities between perceptions of climate change and the acceptability of climate policies. They found great concern for climate change but substantial rejection of the carbon tax.⁴ These studies further confirm the need to implement redistribution to accompany a carbon tax, targeting households whose income is affected the most.

Finally, Ahamada et al. (2017) investigated the impact of a carbon tax in France, at a regional level. They concluded that the tax increases inequalities between regions, but that a region-specific subsidy can compensate for them while reducing CO₂ emissions. They confirmed that a redistribution of tax revenues that takes into account specific regional effects can help make carbon tax reform more progressive. Our article is in the same vein as Ahamada et al. (2017), but with notable differences in the econometric models and the international scope.

3 Data

3.1 Data and variables

We used unbalanced panel data for 19 European countries⁵ for the period 2000-2017 uploaded through the OECD ilibrary portal. The data includes CO₂ emissions per capita (in kilograms - kg) in the residential sector from energy consumption excluding electricity,⁶ obtained from

⁴They also found majority support for stricter norms and green investments.

⁵Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

⁶The data allow us to distinguish carbon dioxide emissions from all fossil-fuel consumption from those from electricity generation. In this paper, we exclude CO₂ emissions from electricity for three reasons: i) CO₂ emissions from residential electricity consumption are already accounted for in the energy production sector; ii) CO₂ emissions from electricity are already regulated by the EU ETS; iii) finally our aim is to carry out a simulation exercise of a carbon tax on fossil fuels.

the International Energy Agency (IEA). Carbon dioxide emissions per capita are derived from fossil energy combustion and reflect the country’s residential energy mix. It is computed as the sum, across all energy sources, of emissions from fuel combustion divided by population. In this context, the drivers of residential energy consumption are the same as those for emissions, and our work is related to the literature on energy consumption.

Our dataset also includes GDP per capita in purchasing power parity in constant 2011 dollars taken from World Development Indicators of the World Bank, and the gas and heating-oil prices in dollars per unit (MWh for natural gas and 1000 liters for heating oil) from the International Energy Agency (IEA). Exchange rates from the European Central Bank were used to convert GDP per capita and energy prices from dollars to euros. To control for weather conditions, we used data from Eurostat on heating degree days. This variable is an indicator of winter severity, and thus of heating requirements.⁷ Population information comes from Eurostat.

3.2 Descriptive analysis

The main descriptive statistics are presented in Tables 1 and 2. They highlight broad disparities between European countries in environmental, economic and weather variables. The level of development and wealth of European countries is illustrative of these differences; some countries such as Poland, Slovakia and the Czech Republic have a per capita GDP of less than €20000, less than a quarter of that of the richest countries such as Denmark and Luxembourg. In-depth scrutiny of the data shows that GDP per capita in Luxembourg is almost ten times that of Poland. The level of CO₂ emissions per capita also differs. CO₂ emissions per capita in the residential sector in Luxembourg are, on average, twenty times higher than those in Sweden. Overall, regarding per capita CO₂ emissions and GDP per capita, we can identify four groups of countries: (i) Northern-European countries with high GDP per capita and low CO₂ emissions per capita (Sweden, Finland and Denmark); (ii) Southern-European countries with low GDP per capita and low CO₂ emissions per capita (Spain, Portugal, Greece); (iii) Eastern-European countries characterized by low GDP per

⁷Heating Degree Days is calculated as the sum of the difference between an indoor reference temperature (usually 18°C) and the average daily outdoor temperature during the heating period (October to April).

capita and high CO₂ emissions per capita (Poland and the Czech Republic for instance); and (iv) Western-European countries characterized by both high GDP per capita and high CO₂ emissions per capita such as Germany, France and the UK.

Table 1: Summary Statistics

VARIABLE	Observations	Mean	SD	Min	Max
Emissions per capita (kg) - <i>e</i>	342	889.79	543.27	14.60	2674.40
GDP per capita (€) - <i>y</i>	342	30077.34	15309.28	6440	84420
Heating Degree Days - <i>hdd</i>	342	2955.41	1049.39	1054.56	6190.94
Gas Price (€/MWh) - <i>pgas</i>	293	58.92	21.70	10.10	122.59
Oil Price (€/thousand liters) - <i>poil</i>	315	736.59	275.93	253.96	1581.78

To fully understand differences and trends in residential CO₂ emissions, we examined additional household energy consumption data from the Odyssee ENERDATA database by end-use and energy source for the countries in our sample for the years 2000 and 2017. The main uses of energy by households at the European level are for heating (64%), water heating (15%), cooking (6%) as well as lighting and electrical appliances (14%). We distinguished four groups of countries with respect to the share of gas and heating oil in total residential energy consumption for heating purposes (see Table 9 in the appendix for heating-energy sources). The first group includes the UK, Netherlands, Luxembourg and Belgium, with a share exceeding 80%. The second group includes countries where this figure is between 65% and 80%, such as Germany, Italy, Slovakia and Ireland. Spain, Greece, France and Austria belong to a third group where the share is around 50%. A final group is made up of countries where the share of gas and heating oil accounts for less than 30%. The latter includes Sweden (2%), Finland and Portugal (8%), Poland (16%), Denmark (20%) and the Czech Republic (27%). The proportion of district heating in Sweden, Finland and Denmark varies between 30% and 50%. It should be noted that the share of electricity for heating accounts for less than 10% in most European countries, except in Sweden (29%) and Finland (24%). Comparison of the data between the beginning and the end of the period (2000-2017) shows that these national characteristics are relatively constant over time and are therefore likely to be captured by the country fixed effects in our econometric models.

Concerning weather conditions, there is a gap of up to 5000 heating degree days between European countries, implying significant differences in terms of heating needs. We observed

Table 2: Means of the variables by country

	<i>e</i>	<i>y</i>	<i>pgas</i>	<i>poil</i>	<i>hdd</i>
Austria	906.02	34845.56	57.69	671.65	3538.40
Belgium	1684.32	32811.67	60.28	566.24	2660.14
Czech Republic	822.26	14337.78	44.28	637.90	3337.51
Denmark	553.24	44396.11	83.14	1084.66	3233.49
Finland	355.43	34396.44	14.88*	717.75	5484.7
France	855.44	30693.33	55.22	655.28	2370.82
Germany	1260.92	31756.67	61.62	581.42	3041.81
Greece	666.37	19255.21	63.39	790.42	1602.67
Ireland	1510.65	39777.78	56.89	707.70	2753.70
Italy	874.37	27135.11	72.50	1114.30	1903.77
Luxembourg	2253.13	77945.00	40.93	529.65	2882.99
Netherlands	1159.22	37833.33	62.51	816.75	2681.62
Poland	904.62	8873.89	42.14	653.00	3394.17
Portugal	200.14	16662.78	73.22	923.04	1223.82
Slovakia	608.80	11617.22	37.59	365.49	3242.65
Slovenia	560.20	17093.89	64.51	785.42	2832.01
Spain	407.95	23003.90	62.56	628.76	1780.09
Sweden	110.04	38970.56	109.63	1051.27	5198.69
UK	1212.77	30090.56	43.05	550.83	2989.85

*The average price of natural gas in Finland must be interpreted carefully as we have only one observation, that of the beginning of the period. The variable names *e*, *y*, *pgas*, *poil* and *hdd* in the first row of the table refer to emissions per capita (kg), GDP per capita (€), gas price (€/MWh), heating-oil price (€/thousand liters) and heating degree days respectively.

that heating needs increase from the South to the North. A comparison of Sweden with Portugal is an interesting illustration of these heterogeneities. On average, Sweden emits half as much CO₂ per capita as Portugal, despite temperatures four times lower and a GDP per capita twice as high. On the other hand, the carbon tax is much higher in Sweden, and it has existed much longer.

Energy prices are also country-specific and differ significantly between European countries. Sweden, Denmark and Italy show the highest energy prices among European countries. Energy prices in these countries appear to be two to three times higher than those observed in Slovakia and the United Kingdom. It appears that energy prices are not proportional to the level of GDP. For instance, gas prices in the United Kingdom are slightly lower than in the Czech Republic, although GDP per capita is more than twice as high. Finally, we note that cross-correlations between energy prices are strong and positive. The pairwise correlation between gas and heating-oil prices in our sample is 0.81. This could produce collinearity issues if we include both energy prices as drivers of CO₂ emissions.

4 The empirical model

We aim to model the determinants of per capita carbon dioxide emissions in the residential sector, which are derived from energy consumption for heating, hot water and cooking (which represent 84.5% of household energy use, Eurostat, 2019), and are still not regulated by the European Commission. We focus on CO₂ emissions from natural gas and heating-oil consumption as apart from electricity, they are the most common energy sources used by European households.

We adapt the static model of CO₂ emissions from the French residential and commercial sectors in Ahamada et al. (2017) to account for short-term dynamics. Their model is an extension of the empirical model of energy consumption in Ang (1987). Ahamada et al. (2017) used various functional forms for the relationship between carbon emissions per capita and GDP per capita to examine whether the cross-sectional income elasticity of CO₂ emissions per capita depends on the level of income per capita. They concluded a monotonic relationship between CO₂ emissions per capita and GDP per capita as income does not

differ considerably between French regions. Many authors justify the introduction of a quadratic term when modeling energy consumption. Ang (1987) and Destais et al. (2009) showed that energy intensity experiences a strong and lengthy growth phase before reaching a turning point. Madlener (1996) reviewed the results of several econometric models of residential energy demand. He pointed out that a log-linear specification of the relationship between energy consumption and GDP suffers from a major drawback due to the underlying assumption of constant elasticity. Moreover, the quadratic form function can be viewed as an approximation of a more complex function and constitutes an alternative solution to non-parametric approaches. We accordingly use a quadratic form function to model the relationship between the logarithm of CO₂ emissions per capita and the logarithm of GDP per capita.⁸

We first consider a static model which will serve as a benchmark. We specify a linear relationship between the logarithm of per capita carbon emissions and the logarithm of GDP per capita and its square to account for a non-constant income elasticity of CO₂ emissions. We add a weather variable as a proxy for heating needs and the prices of gas and heating oil, as these energy sources are close substitutes. This model is static in that it assumes an instantaneous adjustment to new equilibrium values when energy prices or income change. It assumes, for example, that the household can change both its usage rate and appliances, adjusting them instantaneously and jointly to variations in energy prices or income, so that the short-run and long-run elasticities are the same (Filippini, 2011). The static equation of CO₂ emissions per capita is the following:^{9,10}

⁸In a preliminary analysis, we alternately estimated cubic, quadratic and linear functional forms of the relationship between the logarithm of CO₂ emissions per capita and logarithm of GDP per capita. We have then compared the appropriateness of these three functional forms using both i) Student's t-tests for the significance of the cubic and/or the quadratic terms; and either ii) Fisher tests or likelihood ratio tests for model comparison. All these tests confirm rejection of the linear and cubic specifications in favor of the quadratic relationship.

⁹In a preliminary analysis we also considered time-varying fixed effects to capture exogenous shocks that could affect all European countries in the same way. However, the estimated coefficients associated with energy prices became insignificant. This is a common problem that we attribute to collinearity with gas and heating-oil prices. National energy price variations mainly reflect price variations in international energy markets and behave like time-varying fixed effects.

¹⁰The empirical literature using cross-sectional data to estimate energy demand typically includes housing characteristics (energy efficiency and dwelling size). Although our work involves aggregate data, we also considered dwelling size in our preliminary regressions, but the corresponding estimated parameters appeared to be insignificant. The impact of housing characteristics is undoubtedly captured in the country fixed-effects.

$$E_{it} = \alpha + \alpha_{i0} + \alpha_1 Y_{it} + \alpha_2 Y_{it}^2 + \alpha_3 P_{it}^{gas} + \alpha_4 P_{it}^{oil} + \alpha_5 Hdd_{it} + \varepsilon_{it} \quad (1)$$

where i refers to the country and t to the time period. E is the logarithm of per capita CO₂ emissions in the residential sector, Y the logarithm of per capita GDP, P^{gas} and P^{oil} the logarithms of gas and heating-oil prices respectively and Hdd the heating degree days in logarithmic form. In static models using panel data, we account for unobserved heterogeneity using fixed or random effects, and α_{i0} terms allow for unobserved country-specific heterogeneity. To allow more flexibility about their correlation with the other right-hand variables in equation (1), they should preferably be regarded as fixed intercepts (fixed effects), which will capture the impact of any time-invariant country characteristics. The coefficients α_3 , α_4 and α_5 represent the elasticities of CO₂ emissions per capita relative to gas price, heating-oil price and heating needs, respectively. The income elasticity of CO₂ emissions per capita depends on the level of income per capita and equals $\alpha_1 + 2\alpha_2 Y_{it}$.

In a second step, it is interesting to consider that observed CO₂ emissions per capita may differ from their long-run equilibrium, because for instance, the equipment stock cannot adjust easily to the long-run equilibrium. A partial adjustment mechanism allows for this situation. We consequently extend the static model in (1) by introducing a lagged dependent variable as a regressor. We estimate a dynamic panel model that accounts for short- and long-term relationships, producing the following equation:

$$E_{it} = \alpha + \alpha_{i0} + \beta E_{it-1} + \theta_1 Y_{it} + \theta_2 Y_{it}^2 + \theta_3 P_{it}^{gas} + \theta_4 P_{it}^{oil} + \theta_5 Hdd_{it} + \varepsilon_{it} \quad (2)$$

where E is the logarithm of per capita CO₂ emissions in the residential sector, Y the logarithm of per capita GDP, P^{gas} and P^{oil} the logarithms of gas and heating-oil prices respectively, and Hdd the logarithm of heating degree days. Here α_{i0} denotes a full set of country fixed-effects, which will capture the impact of any time-invariant country characteristics, and β is the autoregressive parameter. The error term ε_{it} includes all other time-varying unobservable shocks to per capita CO₂ emissions. The coefficients θ_3 , θ_4 and θ_5 represent the short-term elasticities of CO₂ emissions per capita relative to gas price, heating-oil price and heating needs, respectively. The short-term elasticity of CO₂ emissions per capita relative

to income is country and time specific and equals $\theta_1 + 2\theta_2 Y_{it}$. The corresponding long-run elasticities are derived as the short-run elasticities divided by $(1 - \beta)$.

5 Econometric approach and estimation results

5.1 The static model

We estimate model (1) with country-specific fixed effects using the Within (or LSDV) estimator and adjust the standard errors of the estimated parameters to account for panel groupwise heteroskedasticity and cross-sectional dependence. We use the Driscoll and Kraay (1998) standard errors which are robust to very general forms of cross-sectional dependence. The estimation results appear in Table 3 and show that all the estimated coefficients have the expected sign and are highly significant. Elasticities of CO₂ emissions per capita relative to gas and heating-oil prices equal -0.23 and -0.14 . The elasticity of CO₂ emissions per capita relative to gas price is lower than that found by Ahamada et al. (2017): they estimated the decrease in per capita CO₂ emissions from the French residential and commercial sectors to be 0.37% following a 1% increase in the price of gas.¹¹ Our results are consistent with those in Filippini et al. (2014), who found the price elasticity of energy consumption ranged from -0.26 to -0.19 . The estimated coefficient related to heating degree days, 0.849, shows that milder weather pushes per capita emissions downward. The estimated parameters associated with log GDP per capita and its square show that the income elasticity of CO₂ emissions per capita depends on the level of income per capita.

The country-specific fixed effects here turn out to be correlated with income, national energy prices and heating needs. They capture, among other things, the country's residential energy mixes and housing characteristics. Figure 1 plots these specific effects and reveals that, all else equal, CO₂ emissions of those living in Luxembourg, Belgium, Ireland, Italy and the Netherlands are higher on average than those of people living elsewhere: residents of Sweden, Finland, Portugal and Slovenia have the lowest emissions.

¹¹In Ahamada et al. (2017) the price of heating-oil is excluded from the set of CO₂ emissions drivers because it is highly correlated with the price of gas.

Table 3: Fixed effects (LSDV) estimation results accounting for panel groupwise heteroskedasticity and cross-sectional dependence

Dep. variable: log CO ₂ per capita	LSDV with Driscoll and Kraay SE	
log GDP	9.078***	(1.083)
log GDP squared	-0.444***	(0.063)
log Gas price	-0.232***	(0.045)
log Heating-oil price	-0.140***	(0.034)
log Heating degree days	0.849***	(0.124)
Constant	-44.44***	(5.316)

Note: Standard errors are in (); *, ** and *** refer to the 10%, 5% and 1% significance levels. The dependent and explanatory variables are in logarithmic form.

Figure 1: Estimated country-specific fixed effects from the static model

5.2 The dynamic model

Using the Within (or LSDV) estimator to estimate dynamic panel data models is often inappropriate because it produces biased and inconsistent estimates when the right-hand side equation includes a lagged dependent variable as a regressor. In fact, the lagged variable is correlated with the error term and results in violation of the strict exogeneity assumption. Many studies have proposed a solution to this issue using instrumental variable estimators. Anderson and Hsiao (1982) suggested a simple instrumental variable estimator that corrects for the endogeneity bias. Arellano and Bond (1991) as well as Blundell and Bond (1998) proposed two different estimators based on the general method of moments (GMM). These estimators essentially first-difference the model to eliminate the fixed effects. Thus, the underlying idea of these estimators is that lagged levels and/or additionally lagged differences are valid instruments for the lagged endogenous variable; that is, they are uncorrelated with the transformed error term. A particular issue in GMM estimation is choosing the right number of moment conditions as there is convincing evidence that too many instruments introduce bias while increasing efficiency (Baltagi, 2005). The number of available potential instruments increases with the number of periods T . Therefore, one must reduce the number of lags of the dependent variable to use as instruments to take advantage of the trade-off between the reduction in bias and the loss in efficiency. This is especially true for estimation with small samples. Another problem of these two GMM estimators is that their properties hold for large N , so the estimation results may be inconsistent in panel data with a small number of cross-sectional units. An alternative approach proposed by Kiviet (1995), based on correcting the small sample bias of the Within (LSDV) estimator, has gained wide interest. Indeed, Kiviet (1995), and to a higher level of accuracy Kiviet (1999), proposed a method to correct the LSDV estimator for samples where N is small or only moderately large. Moreover, Judson and Owen (1999) have shown with a Monte Carlo analysis that in dynamic panels characterized by $T \leq 20$ and $N \leq 20$, as in our case, the Anderson-Hsiao and the Kiviet corrected LSDV (LSDVC) estimators are better than the Arellano-Bond GMM estimator. Bun and Kiviet (2003) analyzed the performance of the Kiviet (1999) approximation using simpler formulae, which unfortunately applies only for balanced panels. Fortunately, Bruno (2005) extended the bias correction by Bun and Kiviet (2003) to accommodate unbalanced

Table 4: Estimation results of the dynamic model with fixed effect

Dep. variable: log CO ₂ per capita	Anderson-Hsiao		Arellano-Bond		LSDVC		LSDV	
Lagged log CO ₂ per capita	0.627*	(0.327)	0.722***	(0.048)	0.703***	(0.038)	0.661***	(0.061)
log GDP	2.821	(3.458)	2.163	(2.146)	2.699***	(0.944)	3.009***	(0.833)
log GDP squared	-0.118	(0.168)	-0.099	(0.103)	-0.129***	(0.048)	-0.144***	(0.040)
log Gas price	0.115	(0.077)	-0.021	(0.065)	-0.027	(0.045)	-0.045	(0.048)
log Heating-oil price	-0.070*	(0.038)	-0.128**	(0.054)	-0.114***	(0.031)	-0.112***	(0.031)
log Heating degree days	0.947***	(0.137)	0.890***	(0.096)	0.805***	(0.076)	0.802***	(0.098)
Constant	-0.014	(0.010)	-16.001	(11.370)			-18.847***	(4.255)

Note: Standard errors are in (); *, ** and *** refer to the 10%, 5% and 1% significance levels. Standard errors of the LSDVC estimator are bootstrapped using 1000 iterations.

panels. He also carried out Monte Carlo experiments to assess how unbalancedness affects LSDV bias and its approximations.

Consequently we chose to estimate the dynamic model of per capita CO₂ emissions (2) using three different estimators:¹² the Anderson-Hsiao (AH) instrumental variable estimator, the Arellano-Bond GMM estimator and the corrected LSDV (LSDVC) estimator. The results are presented in Table 4. Table 4 also reports the results from the Within (LSDV) estimator which will serve as a benchmark to discuss the appropriateness of the three competing estimators.

A comparison between the estimated parameter associated with the lagged dependent variable allows us to select the most appropriate approach with consistent estimates. From the literature, it is known that in a dynamic specification with a small number of periods, the coefficient of the lagged variable obtained using OLS is biased upward, whereas the coefficient obtained from the LSDV is invariably biased downward.¹³ From Table 4, we observe that $\hat{\beta}^{AH} = 0.627$ is lower than $\hat{\beta}^{LSDV} = 0.661$. The bias of the Anderson-Hsiao estimator appears to be larger than that of the LSDV estimator. We consequently excluded the Anderson-Hsiao

¹²Judson and Owen (1999) remind us that the literature on the appropriateness of competing estimators has generated conflicting results, showing that the characteristics of the data influence the performance of an estimator. For instance, Arellano and Bond (1991) found that GMM procedures are more efficient than the Anderson-Hsiao estimator, while Kiviet (1995), using a slightly different experimental design, found that the Anderson-Hsiao estimator compares favorably to GMM and concluded that no estimator is appropriate in all circumstances.

¹³For a positive parameter. See Nickell (1981) for a discussion.

estimator from the set of potential consistent estimators. The value of $\widehat{\beta}^{AB} = 0.722$ seems to be overestimated since the coefficient obtained using GMM estimators in small samples, as in our case here ($N \leq 19$, $T \leq 18$) may be biased toward those of the OLS (upward). This is especially true when the number of instruments (22) is as high as or exceeds the number of cross-sectional units. Moreover, although all the estimated coefficients in the Arellano-Bond GMM approach have the expected signs, those associated with the income variables are statistically insignificant. The value of $\widehat{\beta}^{LSDVC}$ from the Kiviet (1995) and Bruno (2005) approaches seems to be the most plausible and appropriate for two reasons. First, $\widehat{\beta}^{LSDVC} = 0.703$ is higher than $\widehat{\beta}^{LSDV} = 0.661$ and thus $\widehat{\beta}^{LSDVC}$ reduces and corrects for the downward bias of the LSDV estimation. Second, $\widehat{\beta}^{LSDVC}$ is slightly lower than the upward biased $\widehat{\beta}^{AB}$. The estimated coefficients obtained from the LSDVC¹⁴ approach are satisfactory in that they all have the expected signs and are highly significant, except for the parameter associated with gas price. This is likely due to the redundancy of the information included in heating-oil and gas prices.¹⁵ One way to overcome the multicollinearity problem is to estimate the model by alternately considering one correlated variable and then the other.

We consequently re-estimated model (2) using the LSDVC estimator, excluding the price of heating-oil from the right-hand side of the equation. The results are shown in Table 5 and are satisfactory insofar as the estimated coefficients have the expected signs, are highly significant and are of magnitudes comparable to those in the column labeled “LSDVC” of Table 4. Slight differences may be related to sample differences due to imbalance in our panel dataset. The estimated parameter associated with gas price is highly significant and of the same magnitude as that of heating-oil price in the column “LSDVC” of Table 4. The value of the coefficient of the lagged variable is slightly higher, and this will of course influence long-run elasticities.

The results reported in Table 4 obtained using the LSDVC estimator indicate that elasticities of CO₂ emissions per capita relative to GDP per capita are country and time specific

¹⁴The analysis is performed assuming a bias correction up to order $O(1/NT)$ and Arellano-Bond as a consistent estimator to initialize the bias correction. The standard errors are calculated through bootstrapping with 1000 iterations.

¹⁵Their estimated pairwise correlation is equal to 0.81 in our sample.

Table 5: LSDVC estimation results of the dynamic model excluding heating-oil price

Dep. variable: log CO ₂ per capita	LSDVC	
Lagged log CO ₂ per capita	0.744***	(0.032)
log GDP	2.082***	(0.863)
log GDP squared	-0.098***	(0.045)
log Gas price	-0.120***	(0.027)
log Heating degree days	0.773***	(0.077)

Note: Bootstrapped standard errors with 1000 iterations are in (); *, ** and *** refer to the 10%, 5% and 1% significance levels.

and depend on the corresponding level of GDP per capita. The conditional relationship between CO₂ emissions per capita and GDP per capita is found to be an inverted U shape with a turning point at €34892 per capita. It should be noted that the long-term elasticities are more than three times greater than the corresponding short-term elasticities.

In the short-run, heating-oil price elasticity is equal to -0.114 .¹⁶ The estimated coefficients of the weather variable (heating degree days) show that greater heating needs drive per capita emissions, which is consistent with the theoretical predictions of Mansur et al. (2008) and Honoré (2018). When we include the price of gas instead of heating oil to avoid multicollinearity, the results in Table 5 show a short-term elasticity of CO₂ emissions per capita relative to gas price of -0.12 . The corresponding long-term elasticities of per capita CO₂ emissions relative to heating-oil and gas prices equal -0.384 and -0.469 and are consistent with the results of Ahamada et al. (2017). Overall, our results are consistent with the energy consumption literature findings that short-run elasticities are lower than long-run elasticities.

We plot country-specific fixed effects $\hat{\alpha}_{i0}$ in Figure 2. This gives a slightly different figure than that of the static model. It shows that, on average and all else equal, emissions in Sweden, Denmark, Austria and Slovenia are lower than emissions elsewhere. Households in Greece, Belgium, Italy, Ireland, Portugal, Luxembourg, France and Poland have the highest emissions. This pattern may be explained in the case of Sweden, for example, by the extensive use of district heating and/or the high carbon tax in place since the early 1990s.

¹⁶Similarly, the results reported in Table 5 indicate that the elasticity of CO₂ emissions relative to gas price equals -0.12 .

Figure 2: Estimated country-specific fixed effects from the dynamic model

More generally, these patterns may reflect the quality of the thermal insulation in housing, or simply habits.

The comparison of the estimation results of both the static and dynamic models highlights differences in the estimated elasticities of per capita CO₂ emissions relative to energy prices and income per capita. This result reflects the problem of inference when the dynamic is not taken into account. The instantaneous adjustment hypothesis concerning the equilibrium behind the static model appears to be too restrictive and does not allow an accurate accounting of how households adjust their CO₂ emissions following changes in their income and/or energy prices.

In light of these results, we conclude that in terms of policy, there are two channels through which the reduction of CO₂ emissions per capita in the residential sector can be achieved: (i) an increase in energy prices through the implementation of taxes based on the carbon content of energy types; (ii) an increase in the per capita wealth of countries, which would tip them into the downward phase of the inverted U-shaped curve with a negative income-elasticity of CO₂ emissions. One way to boost economic growth would be

to build on the energy transition, particularly by improving energy efficiency. Investing in weatherization can create jobs (Perrier and Quirion, 2018). In the next section, we use the estimated parameters from the LSDVC estimates in Table 5 to run a simulation of a European carbon-tax policy.

6 Impact of a European tax on residential CO₂ emissions: a simple illustration

By 2019, eleven European countries had already imposed a carbon tax, without any coordination at the European level (see Table 6). Based on this, the European Association of Environmental and Resource Economists (EAERE) recommended that in parallel to the EU ETS, a carbon tax should be adopted to reduce greenhouse gas emissions in housing. The EAERE’s statement¹⁷ is clearly in line with the 2001 European Commission’s carbon tax project. The European Commission¹⁸ proposed the “introduction of an additional uniform CO₂-related tax: this tax would be added to the taxes already levied under the Taxation Directive Energy and complement the E.U. emission trading system”.¹⁹ This CO₂ tax would be set at €20 per tonne. This rate would be a minimum for each member state.

¹⁷“EU economists call for carbon taxes to hit earlier net zero goal”, Financial Times, June 28, 2019.

¹⁸A uniform carbon taxation in Europe was initially suggested in the 1990’s, first in the White Paper on “Growth, competitiveness and employment” (European Commission, 1993) and then in Drèze and Malinvaud (1994). This gave rise to considerable debate, mainly on the macroeconomic consequences of eco-taxation.

¹⁹Impact Assessment Accompanying document to the Proposal for a Council Directive amending Directive 2003/96/EC restructuring the Community framework for the taxation of energy products and electricity - COM (2011) 169 final - SEC (2011) 410 final, Commission Staff Working Paper, European Commission, 2011.

Table 6: Carbon taxation in Europe in 2019

Country	Carbon tax level in € per tCO ₂ in 2019	Year of Implementation
Finland	62	1990
Norway	49	1991
Sweden	109	1991
Denmark	24	1992
Ireland	26	2010
UK	20	2013
Slovenia	17	1996
Portugal	24	2015
Spain	15	2014
Poland	<1	1990
France	45	2014

Source: World Bank Group, 2020, State and Trends of Carbon Pricing.

In this illustration, we assume that a carbon tax of €20 per tonne was implemented Europe-wide in 2017. Given the carbon-emission factors for gas and heating oil from the IPCC, which are 2.3 and 3.2 tonnes per tonne of oil equivalent (toe) respectively, the carbon tax corresponds to an increase of €3.95 per MWh of natural gas and €53.20 per thousand liters of heating oil. It thus represents a slight increase in energy prices. In 2017, this gas price increase would range from 3% – 4% for Sweden and Denmark to 8% for the UK and 9% for Luxembourg. Likewise, the increase in heating-oil prices would range from 4% in Denmark to 9% in the UK. We analyzed the impact of this tax on CO₂ emissions and tax revenues in each European country using the elasticities calculated above (Table 5). We focused on the immediate consequences of carbon taxation on energy prices, which is one limitation of our analysis as it allows for short-term analysis only.

As mentioned in a number of studies (Bureau (2012), Douenne and Fabre (2019) and (2020)), the political economics of a carbon tax are key to its successful implementation. One way to increase the probability of success is to make the tax progressive by reducing costs for those who are most affected. It suggests that agents who bear a heavier cost should be compensated accordingly. In our case, this means that country-specific fixed effects should be considered, as they are constant over time and reflect the structural differences between countries.

We first use the results in Table 5 to predict CO₂ emissions per capita in the residential sector at the country level, considering the carbon tax of €20 per tonne implemented in 2017. We calculate emissions for 2017 using the following equation (see equation 2):

$$\widehat{E}_{i2017} = \hat{\alpha}_{i0} + 0.744E_{i2016} + 2.082Y_{i2017} - 0.098(Y_{i2017})^2 - 0.12P_{2017}^{gas} + 0.773Hdd_{i2017}$$

where \widehat{E}_{i2017} is the predicted logarithm of emissions per capita for 2017, P_{2017}^{gas} the logarithm of the new gas price in 2017 including the carbon tax at a rate of €20 per tonne of CO₂, and $\hat{\alpha}_{i0}$ the estimated country fixed-effect. In a second step, we calculate the corresponding national tax revenues and compare the burden of the tax by measuring the tax revenues to GDP ratios.

Table 7 reports CO₂ emissions per capita with and without carbon taxation and the relative abatement in CO₂ emissions.²⁰ We then measure the burden of the policy by calculating the ratio of national tax revenues to GDP. We observe striking inequalities between countries. For example, Poland contributes 0.17% of its GDP while Portugal contributes less than 0.02%; France contributes almost 0.04% (see Table 7).

Not surprisingly, the introduction of a carbon tax reduces CO₂ emissions in all countries, but with significant differences (Table 7). In general, the abatement rates are different across countries: Luxembourg (−1.32%), the UK (−1.21%), Germany (−1.17%) and Belgium (−1.21%) have the highest abatement rates, while those of Denmark (−0.64%), Portugal (−0.69%), the Netherlands (−0.72%) and Italy (−0.64%) are the lowest. These differences are probably due to the marginal impacts of this carbon tax on total energy prices, which differ from country to country, depending on pre-existing national taxes. Indeed, the same tax per unit of CO₂ emitted is added to the domestic energy prices in all countries.²¹ Its introduction will lead to a relative increase in energy prices, which will be all the greater the lower the initial price is. We also see huge differences between countries on the budgetary consequences of this European carbon tax. Revenues from the tax represent 0.17% of GDP in Poland, and only 0.017% in Denmark, i.e., 10 times less. Some countries

²⁰In this section, we limited our sample to 16 countries (out of 19) as data on 2017 gas prices are not available for Finland, Slovakia and Sweden.

²¹The price increase is €3.95 per MWh of natural gas and €53.20 per thousand liters of heating oil in each country.

(Poland, the Czech Republic, UK, Belgium) will bear the highest costs of this policy due to their heating needs and residential energy mix. This high tax burden could be an argument against the adoption of a European carbon tax.

To increase the probability of carbon tax acceptance in all countries, we calculated the monetary compensation required to ensure equal relative contributions among European countries. We considered a tax-fairness principle in which all European countries contribute the same proportion of their GDP. We calculated the average 2017 tax levy for all countries corresponding to a uniform carbon tax of €20 per tonne and assumed that each country must achieve this average tax levy (Table 8).

Table 7: Carbon emissions with and without tax

	CO ₂ emissions per capita without tax	CO ₂ emissions per capita €20 carbon tax	CO ₂ emissions (in %) €20 carbon tax	Tax revenue/GDP
Austria	763.97	756.35	-0.9967%	0.0408%
Belgium	1425.21	1408.01	-1.2067%	0.0797%
Czech Republic	799.37	790.80	-1.0723%	0.0920%
Denmark	386.69	384.23	-0.6361%	0.0163%
France	668.83	662.56	-0.9369%	0.0409%
Germany	1080.60	1067.99	-1.1675%	0.0603%
Greece	473.13	469.38	-0.7928%	0.0539%
Ireland	1238.98	1225.74	-1.0684%	0.0452%
Italy	772.70	767.74	-0.6424%	0.0579%
Luxembourg	1906.06	1880.92	-1.3190%	0.0456%
Netherlands	945.57	938.74	-0.7222%	0.0461%
Poland	996.08	985.36	-1.0756%	0.1667%
Portugal	152.31	151.26	-0.6930%	0.0171%
Slovenia	365.66	362.31	-0.9158%	0.0373%
Spain	334.41	331.02	-1.0122%	0.0271%
UK	993.67	981.66	-1.2090%	0.0605%

Basically, this accompanying policy consists of a redistribution of carbon-tax revenues. The ratio of total tax revenues to total GDP over the whole panel is 0.05535%.²² Finally, we calculated the transfers for an equal contribution rate for all countries. We found that most countries would have to contribute over and above the €20/tonne of CO₂ tax rate. For example, French households would have to pay €4.66 per capita per year. Poland is

²²I.e., the average contribution rate, if it were to be equal among all countries after compensation, should be set to 0.05535%.

the main beneficiary (€13.16 per capita per year) while Denmark is the highest contributor (€18.37 per capita per year).

Table 8: Tax revenues per capita, contribution rate (tax revenue/GDP) and transfers per capita

	Tax revenues €20 carbon tax	Contribution rate €20 carbon tax	Lump-sum Transfers equal-contribution rate (0.05535%)
Austria	15.13	0.0408%	5.40
Belgium	28.16	0.0797%	-8.60
Czech Republic	15.82	0.0920%	-6.29
Denmark	7.68	0.0163%	18.37
France	13.25	0.0409%	4.66
Germany	21.36	0.0603%	-1.75
Greece	9.39	0.0539%	0.25
Ireland	24.51	0.0452%	5.51
Italy	15.35	0.0579%	-0.69
Luxembourg	37.62	0.0456%	8.07
Netherlands	18.77	0.0461%	3.77
Poland	19.71	0.1667%	-13.16
Portugal	3.02	0.0171%	6.74
Slovenia	7.25	0.0373%	3.51
Spain	6.62	0.0271%	6.89
UK	19.63	0.0605%	-1.67

The results in Table 8 show that the redistribution provides a premium to the highest polluters. Despite the low level of CO₂ emissions per capita in Denmark and Portugal (due to environmentally friendly behavior, high energy prices or favorable weather conditions, for example), these countries would have to increase their contributions for fiscal equity objectives. These results shed light on the trade-off between fiscal equity and environmental efficiency objectives of the carbon tax policy. Indeed, the goal of the redistribution is to equalize the ex-post fiscal efforts across countries. This equity condition will likely make the policy more acceptable in the poorest countries and/or high-emitting countries but may be counterproductive from an environmental point of view. Some countries with high emission rates (like Belgium) would receive compensation from countries with lower emissions. In a way, this redistribution policy may imply environmentally friendly countries compensate

highly polluting countries, regardless of the causes of CO₂ emissions (temperature, GDP, energy mix, etc.). The redistribution also compensates the poorest and coldest countries (like the Czech Republic and Poland), which are usually against any European carbon taxation project. Bauer et al. (2020) arrived at the same conclusion regarding the cap-and-trade policies when uniform carbon prices are considered. Dorband et al. (2019) found that distributional effects of carbon pricing tend to be progressive in low-income countries. The latter policy is effective in reducing carbon emissions, but tends to impose relatively high costs on the poorest countries. They argued that financial transfers between countries could help correct this efficiency-sovereignty conflict.

Finally, how these payments are used and redistributed by the receiving countries will be fundamental, but is not taken into account in this article. For example, it could be a conditional payment on investment in green technologies or the thermal renovation of buildings. Another limitation which represents an extension for future work would be to consider within-country inequalities.

7 Conclusion

This paper disentangles the determinants of residential CO₂ emissions in Europe and shows that CO₂ emission abatement may be achieved through two transmission channels: income and energy prices. Indeed, above a certain per capita income threshold, any increase in wealth should lead to a decrease in emissions; on the other hand, since the elasticities of CO₂ emissions relative to energy prices are negative, an increase in price, caused by a change in carbon taxation, implies a reduction in emissions. We have highlighted the geographical and economic differences between European countries (particularly in terms of GDP and heating needs), and their consequences for the implementation of carbon taxes. We have shown that a homogenous carbon tax rate implies differences in the tax burden that increase inequalities among countries. We then considered a compensation scheme that European governments may implement to correct for the regressive characteristics of the carbon tax. We have shown that lump-sum transfers can compensate for these inequalities. We conclude that this policy may help implement environmental policy without compromising its social

acceptability. This proposal is important at a time when discontent with climate policies is becoming a major social and political obstacle to the fight against climate change. The redistribution of revenues to the countries most heavily penalized by the carbon tax (the most polluting) can also be accompanied by specific conditions, such as the requirement to invest in new green technologies, renewable energy or thermal renovation. This strategy would accelerate the decrease in emissions by further influencing household behavior.

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Appendix

Table 9: Energy consumption for heating by type of fuel in the residential sector

	2017														2000														
	Coal		Oil		Gas		Heat		Wood		Elec		Total (Mtoe)		Coal		Oil		Gas		Heat		Wood		Elec		Total (Mtoe)		
	%	%	%	%	%	%	%	%	%	%	%	%	100%	%	%	%	%	%	%	%	%	%	%	%	%	100%	%		
Austria	0.34	22.13	26.55	13.35	31.54	6.08	4.756	4.28	34.31	19.80	7.59	28.03	5.98	4.575	1.32	38.56	47.24	0.12	9.67	3.10	5.950	1.46	40.08	48.08	0.15	7.03	3.20	6.808	
Belgium	1.32	38.56	47.24	0.12	9.67	3.10	5.950	1.46	40.08	48.08	0.15	7.03	3.20	6.808	15.64	0.46	26.71	13.89	36.86	6.43	4.765	18.12	1.10	35.56	17.75	20.39	7.07	4.674	
Czech Republic	15.64	0.46	26.71	13.89	36.86	6.43	4.765	18.12	1.10	35.56	17.75	20.39	7.07	4.674	0.00	5.39	15.42	43.89	31.95	3.35	3.811	0.03	21.47	18.86	40.82	13.98	4.84	3.473	
Denmark	0.00	5.39	15.42	43.89	31.95	3.35	3.811	0.03	21.47	18.86	40.82	13.98	4.84	3.473	0.07	7.38	0.61	35.31	31.86	24.77	3.379	0.32	21.50	0.62	37.09	23.71	16.77	2.809	
Finland	0.07	7.38	0.61	35.31	31.86	24.77	3.379	0.32	21.50	0.62	37.09	23.71	16.77	2.809	0.85	14.97	36.79	4.53	31.55	11.31	26.250	1.57	27.65	33.32	4.85	22.10	10.51	30.081	
France	0.85	14.97	36.79	4.53	31.55	11.31	26.250	1.57	27.65	33.32	4.85	22.10	10.51	30.081	1.41	28.55	50.25	11.09	6.15	2.55	35.488	2.28	37.94	41.93	6.13	7.82	3.90	46.467	
Germany	1.41	28.55	50.25	11.09	6.15	2.55	35.488	2.28	37.94	41.93	6.13	7.82	3.90	46.467	0.08	43.64	11.93	1.95	32.65	9.73	2.609	0.45	72.05	0.13	0.89	20.05	6.42	3.149	
Greece	0.08	43.64	11.93	1.95	32.65	9.73	2.609	0.45	72.05	0.13	0.89	20.05	6.42	3.149	18.87	48.86	24.92	0.00	1.61	5.74	1.668	30.66	43.77	19.08	0.00	0.98	5.52	1.770	
Ireland	18.87	48.86	24.92	0.00	1.61	5.74	1.668	30.66	43.77	19.08	0.00	0.98	5.52	1.770	0.00	7.15	60.12	3.58	28.72	0.42	22.036	0.31	28.10	64.68	0.00	6.57	0.34	17.846	
Italy	0.00	7.15	60.12	3.58	28.72	0.42	22.036	0.31	28.10	64.68	0.00	6.57	0.34	17.846	n.a.	34.98	54.23	1.41	5.16	4.23	0.426	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Luxembourg	n.a.	34.98	54.23	1.41	5.16	4.23	0.426	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.00	0.55	85.44	4.34	7.18	2.50	6.552	0.06	0.99	90.67	2.26	4.47	1.55	7.485	
Netherlands	0.00	0.55	85.44	4.34	7.18	2.50	6.552	0.06	0.99	90.67	2.26	4.47	1.55	7.485	44.44	0.65	15.03	20.80	18.23	0.86	13.121	35.78	2.98	11.24	32.07	16.74	1.18	12.214	
Poland	44.44	0.65	15.03	20.80	18.23	0.86	13.121	35.78	2.98	11.24	32.07	16.74	1.18	12.214	n.a.	6.85	1.44	0.00	73.87	17.84	0.550	n.a.	3.80	0.48	0.00	84.42	11.32	0.693	
Portugal	n.a.	6.85	1.44	0.00	73.87	17.84	0.550	n.a.	3.80	0.48	0.00	84.42	11.32	0.693	2.13	0.54	70.60	21.38	2.49	2.86	1.303	2.71	0.61	76.70	16.59	0.01	3.39	1.713	
Slovakia	2.13	0.54	70.60	21.38	2.49	2.86	1.303	2.71	0.61	76.70	16.59	0.01	3.39	1.713	0.01	14.94	12.56	9.32	59.16	4.02	0.712	0.64	41.61	5.83	10.73	39.54	1.65	0.753	
Slovenia	0.01	14.94	12.56	9.32	59.16	4.02	0.712	0.64	41.61	5.83	10.73	39.54	1.65	0.753	1.05	30.24	21.09	0.00	40.28	7.33	6.168	1.91	33.62	15.76	0.00	32.40	16.31	6.165	
Spain	1.05	30.24	21.09	0.00	40.28	7.33	6.168	1.91	33.62	15.76	0.00	32.40	16.31	6.165	n.a.	1.10	0.69	47.02	21.30	29.89	4.179	n.a.	23.10	1.02	34.19	15.28	26.42	4.913	
Sweden	n.a.	1.10	0.69	47.02	21.30	29.89	4.179	n.a.	23.10	1.02	34.19	15.28	26.42	4.913	2.13	8.17	74.36	1.12	7.70	6.51	23.209	5.44	8.97	78.84	0.16	5.87	28.364		
UK	2.13	8.17	74.36	1.12	7.70	6.51	23.209	5.44	8.97	78.84	0.16	5.87	28.364	28.364	5.91	15.36	44.83	9.42	19.59	5.83	8.786	5.74	25.14	43.93	7.70	12.06	6.07	10.220	
Means	5.91	15.36	44.83	9.42	19.59	5.83	8.786	5.74	25.14	43.93	7.70	12.06	6.07	10.220															

Note: Units, share in % and Total in Mtoe. Sources: Authors' calculations, data from Odyssee, ENERDATA; detailed sources for each country in order of appearance TU-IEW, SPFEco, ENVIROS, MPO, CZSO, DEA, ODYSSEE, MEDDE, AGEb, ISI, Calculated, SEAL, MISE, STATEC, SP, ODYSSEE, SOSR, JSLEEC, IDAE, STEM, ODYSSEE.