CHIPS
Climate Change Impacts and Policies in Heterogeneous Societies

REPORT ON DELIVERABLE D3.1

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JPI Climate AXIS

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Empirical Estimates of the Regressivity or Progressivity of Carbon Pricing for Different Classes of Goods

Introduction

We have been studying distributional effects for households in the context of the CHIPS program. We developed a methodology for empirical analyses while also developing a microsimulation tool in D3.2. The main application has been to study the effect on the prices of numerous services and goods of carbon pricing and then study the effects on various distributional implications in EU countries (Feindt et al., 2021). We also studied this topic in Mexico (Labandeira et al., 2022). We are furthermore looking into new work on price effects of goods and hoping to see the effects of COVID lockdown on individual rates of inflation which will serve to illustrate mechanisms behind distributional effects of differential price changes (Ewald et al., forthcoming).

Overview

The overall purpose of WP3 is to study distributional effects for households. Deliverable 3.1 develops the methodology for empirical analyses while D3.2 develops a microsimulation tool. The main application in D3.1 has been to study the effect on the prices of numerous services and goods of carbon taxation and then study the effects on various aspects of distribution in EU countries. D3.1 aimed to estimate empirically the regressivity or progressivity of carbon pricing for different classes of goods. This task plays a central role in the overall CHIPS program of analyzing distributional concerns although the focus here is on the distributional concerns of policy rather than of climate damages per se, much of the methodology is however the same. The main published paper doing this was "**Understanding regressivity: Challenges and opportunities of European carbon pricing**" (Feindt et al., 2021). The results of this paper are well summarized in its abstract:

We examine how a European carbon price will affect citizens by studying the carbon tax incidence in 23 countries of the EU. At the national level, the distributional impact prior to revenue recycling is largely neutral, sometimes progressive. At an aggregate EU level, however, the impact is regressive because some low-income countries would be highly impacted if subjected to a common EU carbon price. While national redistribution can do much to make EU incidence progressive, we show that European-wide redistribution is more effective for especially affected households. We offer two indicators to offset regressive distributional effects of EU climate policy such as the recently proposed Green Deal. The first renders the tax burden proportional; the second focuses on compensating the households most seriously affected. Including both indicators in European redistribution makes for a *better representation of the initial burden of carbon pricing and could make the policy more salient for citizens.*

The paper has been published in a reputable journal that is central to the energy and climate debate and has already been well cited and is an important cornerstone for our work. Considering the unfortunate but prevalent critique and resistance against climate policy – which is often framed in terms of distributional effect, it is important to analyze also the distributional effects of climate policy. In other tasks we will be developing the methodology further to also look at the distributional effects of climate change and damages. The deviations from the original plan for D3.1 are quite minimal. We focus on European countries and on various energy carriers. Instead of quintiles we study deciles. In the original proposal for D3.1 we also propose to perform similar analyses for comparative purposes in a number of Latin American countries. We have in practice focused this work on Mexico and written a paper "**Distributional impacts of carbon taxation in Mexico"** (Labandeira et al., 2022). We have however not yet been able to fully complete theoretical modeling of complementarities between capital goods and energy nor have we yet been able to work fully on the effects of for instance flooding since we have not had major flooding in the area where we have detailed prices. We are however looking in new work at price effects of goods and hoping to see the effects of the COVID lockdown on individual rates of inflation which will serve to illustrate the mechanisms behind distributional effects of differential price changes (Ewald et al., forthcoming).

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Understanding regressivity: Challenges and opportunities of European carbon pricing☆

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ABSTRACT

We examine how a European carbon price will affect citizens by studying its incidence on households in 23 countries of the EU. At the national level, the distributional impact before revenue recycling is mainly neutral, sometimes progressive. At an aggregate EU level, however, the impact is regressive because some low-income countries would be strongly affected by the carbon price. While national redistribution can yield a progressive EU incidence, we show that European-wide redistribution is more effective for the most affected households. We offer two indicators to offset regressive distributional effects of EU climate policy, such as the recently proposed Green Deal. The first renders the tax burden proportional; the second focuses on compensating the households most severely affected. Including both indicators in European redistribution makes for a better representation of the initial burden of carbon pricing and could increase public acceptability.

1. Introduction

The European Union (EU) has major climate-policy ambitions, and the European Commission's (EC) Green Deal proposal extends these ambitions further, trying to manifest the EU as a global leader in climate-change mitigation (EC, 2019). The central components of the deal would increase the EU's midterm reduction target from 40% to at least 55% by 2030, aiming at EU-wide climate neutrality by 2050. The measures proposed by the EC could impose significant mitigation costs on European households. Yet, little is known about how these costs will be distributed across countries and income groups. Our analysis provides new estimates of the incidence of a European carbon price and its distributional outcomes, both at the national and the European level. It further indicates how tax revenues can be used to alleviate the adverse distributional effects on selected households.

Carbon pricing, valid across all member states, is central to EU climate policy. This instrument enjoys widespread support from academia (see e.g. Fullerton et al., 2010; Tirole, 2012; Golosov et al., 2014; Nordhaus, 2015; Hassler et al., 2018) as well as from international institutions (e.g. IMF, 2019) and has recently been shown to generate large efficiency gains for the EU (Parry, 2020).[1] Under the Green Deal, the European Emissions Trading Scheme (EU ETS), the EU's central carbon pricing instrument, will be strengthened and its sectoral coverage possibly extended (EC, 2019). Europe has long imposed relatively high taxes on fossil fuels for road transport (Sterner, 2007), and an increasing number of EU countries are introducing more general carbon taxes (Government of the Netherlands, 2019 & Federal Government of Germany, 2019). The Commission also proposes border carbon

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[1] Carbon pricing might require complementary policies that cope with other market failures or governmental limitations. This may lead to different optimal policy designs between regions, countries and even over time (Stiglitz, 2019).

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adjustments so that prices of imports reflect their carbon content (EC, 2019).

The combination of a stricter EU ETS with carbon taxes for non-ETS sectors and border tax adjustments brings us closer to a situation where all goods and services are taxed and full carbon accounting increases in relevance. We adopt this approach here and assume full taxation of direct emissions and those embedded in consumption also when the products are produced elsewhere. Such comprehensive carbon pricing might need to be combined with measures that help citizens cope with the transition to a low-carbon economy. One of the advantages of carbon pricing is that the revenue raised in taxes can be recycled to reduce the impact for households or industries. Such recycling has already been a central tool within the EU-ETS (Dorsch et al., 2019). In the context of the Green Deal, the Just Transition Mechanism, with the Just Transition Fund of 17.5 billion EUR as its central component, will provide additional funds for the regions and sectors most seriously affected by more ambitious climate policy (EC, 2021a). In this paper, we discuss the role of the burden of carbon pricing on consumers, i.e. how much a consumer's expenditure increases due to price increases from the tax. Our central scenario assumes no behavioral adjustments of the economy and is relevant for political decision making when households evaluate a policy based on the status quo of consumption patterns. The burden on consumers is an important indicator for policy as it represents the direct and visible impact of the tax, and shows how revenue could be recycled to offset adverse effects from increased prices.

This seems particularly important, as carbon pricing has been subject to public and political opposition in the past (see e.g. Andersen and Ekins, 2009; Carattini et al., 2018). One important example of public opposition is the yellow-vest movement in France that has had severe impacts on French climate policy. According to a survey by Douenne and Fabre (2020), French people expressed that while they support efforts to limit climate change, they are opposed to increased taxes on transport fuels. Possible reasons are the expected distributional concerns (e.g. severe effect for the middle class and rural households), the lack of affordable green options and possible inefficacy of the policy. The yellow-vest protests highlight the importance of looking more closely at the social and economic factors underlying political acceptability and its relation to fairness, both actual and perceived (see Carattini et al., 2018). It also highlights the importance of a salient revenue recycling scheme that can increase trust in the government (Klenert et al., 2018; Maestre-Andrés et al., 2019) and thereby increasing the support for environmental policies (Criqui et al., 2019). In addition, communicating the environmental and distributional effects of the policy could increase public knowledge about the policy and also raise the level of support (Douenne and Fabre, 2020).

We quantify the initial effects of carbon pricing on households with a microsimulation based on a multi-regional input-output (MRIO) approach (see, e.g., Dorband et al., 2019; Vogt-Schilb et al., 2019). We use data from the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2016), GTAP 9, transformed into an MRIO to calculate the indirect industrial and direct emissions associated with household consumption. Household expenditure patterns are provided by the EUROSTAT Household Budget Survey (HBS) for 23 EU countries, which are mapped to the GTAP sectors and serve to derive carbon intensities. Assuming an exogenous carbon price increase of 25 EUR/tCO2, which corresponds to a price increase from 2010 to almost current levels, we calculate the additional tax burden per household. Finally, households are aggregated to expenditure deciles either at a national or at a European level.[2] Beyond these national and European distributions, we analyze the distributional impact for some special groups that might lack mitigation options. To analyze this concern, we disentangle the drivers of the carbon-tax burden on households in terms of economic sectors and the rural/urban divide. In addition, we identify households with a particularly high burden from the tax. Based on our findings, we propose different redistribution schemes that offset adverse distributional effects on European households.

We confirm our central results in a scenario where consumers react to the price increases based on elasticities estimated in previous literature. In addition, we relax our main assumptions in a set of alternative scenarios that include carbon pricing for domestic emissions only (no border carbon adjustment), EU-ETS policy only (no border carbon adjustment and no sectoral expansion), and evaluating the burden based on current income. All scenarios indicate that the carbon tax is regressive at the level of the whole EU. At the national level, however, a comprehensive carbon price on all goods (even imported) would have a mostly neutral or even progressive impact. The drivers of the regressive pattern at the EU scale are high average carbon tax burdens in some low-income countries (located mainly in Eastern Europe). It turns out that the monetary transfers needed to offset the regressive pattern are relatively small (less than 7% of total revenues). We show that national and European equal per capita redistribution can turn the EU incidence progressive, with European equal per capita redistribution being more effective for the most affected households.

The aim of our study is thus to understand the incidence of comprehensive carbon pricing on European households and to discuss how this understanding can improve policy design. The paper proceeds as follows. In Section 2, we relate our study to previous literature. Section 3 explains the methodology and the data used to derive carbon-tax incidence. Section 4 presents our results: we look at European and national carbon tax incidences (4.1), redistribution schemes (4.2), and consumers with a high tax burden (4.3). A technical discussion of our modeling assumptions and sensitivity analyses can be found in Section 5. Section 6 concludes.

2. Literature

Our analysis builds on previous studies of the carbon tax incidence that evaluate the effects of this policy in single countries. A large part of this literature models demand-side effects only, using microsimulation and assuming either no change in demand (Metcalf, 1999; West and Williams, 2004; Renner, 2018; Dorband et al., 2019) or including demand-side responses (Burtraw et al., 2009; Datta, 2010; Douenne, 2020), which are the approaches taken in the present analysis. Within this literature, we extend studies that analyze single EU-member countries (Labandeira and Labeaga, 1999; Callan et al., 2009; Feng et al., 2010; Farrell, 2017; Berry, 2019) or a number of selected European countries (Symons et al., 2002). While most of the EU-based estimates focus on specific countries in Northern, Western and Southern Europe like Ireland, Sweden, France and Spain, we provide estimates of the carbon tax incidence for 23 of the 27 EU member countries. This includes countries like Poland, Romania, Greece and Bulgaria where evidence so far is sparse. Finding that the incidence is mostly neutral to progressive on a national level is thus of direct relevance to policy makers that wish to address distributional consequences of stronger carbon taxation within the Green Deal in their country. In addition, all incidences reported in our study are comparable across countries because they are consistently built from the same model.

Most importantly, we extend the previous literature by estimating the carbon tax incidence based on European expenditure deciles, and thus go beyond studies that focus on national distributions. One exception is Sager (2019a), who performs an analysis of the European carbon-tax incidence and finds it to be regressive. The study confirms our finding that the regressive effect at the EU level is not due to national regressivity but to inter-country differences. While Sager's study constructs average household characteristics on the percentile level of the income distribution, our study uses micro-level household budget surveys of nearly all EU countries, and thereby estimates the impact of a carbon tax on individual household data. We thus provide new evidence

[2] We construct the expenditure deciles based on a Purchasing Power Parity (PPP) and the modified OECD adult equivalent scale.

on international equity when pricing carbon in Europe. In addition, our modeling approach allows us to study horizontal equity, and we identify especially affected households among the European distribution, which is a highly policy relevant measure of inequality (see e.g. Douenne and Fabre, 2020). Beyond the equal-per-capita redistribution that Sager (2019a) analyzes as well, we introduce two new indicators for European redistribution that alleviate inequality concerns: targeted transfers that render the incidence neutral on a European level and the number of especially affected households in each European country.

Apart from taxation that directly targets carbon dioxide emissions, which we analyze below, many studies focus on proxies like fuel taxation or other sectoral climate policy in multiple European countries. Some studies again estimate national distributions. Sterner (2012a) compares the impact of fuel taxation across different European countries, finding that fuel taxation mostly tends to be neutral. Flues and Thomas (2015) estimate the impact of different energy taxes in European countries. Ekins et al. (2011) show the distributional consequences of sectoral expansion of the European Emissions Trading Scheme in the context of an environmental tax reform, and evaluate the distributional effects across European income quintiles and within European countries. Kosonen (2013) finds a regressive effect of a 10% price increase in electricity and gas prices across EU income deciles. Our study adds to these previous estimates by showing the effect of comprehensive carbon pricing across EU households.

3. Methods

This section describes both the economic and technical concepts behind our analysis and the underlying datasets. We start by introducing the basic concepts of input-output analysis, which is used to derive carbon footprints. Afterwards, we briefly present the characteristics of the MRIO database (GTAP) and the household database (HBS) we use. We then describe the matching procedure between these two databases and the derivation of the carbon tax burden.

3.1. Input-output analysis

Our analysis is based on standard MRIO analysis, see e.g. (Miller and Blair, 2009). The structure of MRIO data, as it implicitly refers to network data, allows to accurately account for the global supply chain structure. MRIO data consists of an inter-industry flow matrix $Z \in \mathbb{R}^{(m \cdot n) \times (m \cdot n)}$, where m is the number of sectors, n is the number of regions, and the final demand vector $Y \in \mathbb{R}^{m \cdot n \times n}$. Single entries of Z, such as ${z_{r1,s1}}^{r_2,s_2}$ reflect the monetary value of flows originating from sector $s_1$in region r_1 and going to sector s_2 in region r_2. Analogously, ${y_{r1,s1}}^{r_2}$ corresponds to the monetary flows from sector s_1 of region r_1 into final demand in region r_2.

The technology matrix $A \in \mathbb{R}^{(m \cdot n) \times (m \cdot n)}$ consists of single entries ${a_{r1,s1}}^{r_2,s_2}={z_{r1,s1}}^{r_2,s_2}/o_{r2,s2}$, where $o_{r_2,s_2} = \sum_s \sum_r \left(z^{r,s}_{r_2,s_2} \right) + \sum_r y^r_{r_2,s_2}$ is a sector's total output. A enables the calculation of the Leontief inverse $L = (I - A)^{-1}$, where I denotes the identity matrix (Leontief, 1936). L reflects all pre-products that have been used at some stage during the production process.

Let $F \in \mathbb{R}^{m \times n}$ denote the CO_2 emissions vector, with elements $F_{r,s}$, which refer to the total emissions released by sector s in region r. Dividing F entry-wise by the corresponding total sectoral output results in vector f, reflecting the CO_2 emissions associated with the production of one USD of output. This is nothing other than 'embodied' emissions intensity.

GTAP reports final demand for households separately and accounts for households' direct emissions. Let ${F_{r1,\ s1}}^{dir}$ denote the direct emissions of households in region r_1 for sector s_1. Let Y^{HH}denote final consumption due to households. The indirect emissions associated with household consumption in region r_1 for sector s_1 are then

$$F^{ind}_{r_1,s_1} = \sum_{r'} \sum_{s'} \sum_{r} f_{r',s'} L^{r,s1}_{r',s'} y^{HH\ r_1}_{r,s_1}.$$

Finally, we need to add the direct emissions, resulting in the total amount of emissions associated with household consumption ${F_{r1,\ s1}}^{HH}$, which is

$$F^{HH}_{r_1,s_1} = F^{dir}_{r_1,s_1} + F^{ind}_{r_1,s_1}.$$

3.2. Data

3.2.1. GTAP

For the calculation of emission intensity from household consumption, we use GTAP 9. This database is transformed into an environmentally extended MRIO model, with the procedure proposed by Peters et al. (2011) and Andrew and Peters (2013). This raw-database covers 140 regions and 57 sectors and consists of harmonized national input-output tables. In addition, it accounts for trade data. We use the base year 2011 to assess total emissions associated with household consumption in the EU, as it is closest to the base year in the household survey. An overview of specific data content of the GTAP database is given in Peters et al. (2011). We follow their approach and use their suggested treatment of international margins and taxes. Finally, we distribute the emissions related to international transportation as Peters et al. (2011) suggest in their 'endogenous international transportation pool approach'.

3.2.2. HBS

The HBS from Eurostat is a national expenditure survey in the EU for all member states (plus Serbia and the United Kingdom) (EC, 2021b). The main goals of this survey are estimating living conditions in the EU and providing data for macroeconomic indicators (e.g. consumer-price indices to measure inflation). The HBS collects data every five years, the latest collection round was in 2015. As the harmonization and publication process of the 2015 round is not yet complete, we build our analysis on 2010 HBS data. The main advantages of this dataset are that all the member states provide their data in line with the same expenditure classification and that Eurostat harmonizes the data with respect to the base year. The expenditure classification follows the COICOP-HBS structure (four levels with 5-digit codes). One drawback is that the data is not fully comparable because of residual differences in data collection between the countries. Examples are the choice of a probability design vs. non-probability schemes, heterogeneous sampling errors, coverage errors, and differences in the calculation of self-imputed rents. Data issues with Czech Republic and Sweden force us to exclude both from the central scenario.[3] In addition, data for The Netherlands and Austria are missing from the 2010 HBS round (EC, 2015). Nevertheless, Eurostat's joint framework increases comparability and enables us to use a harmonized and consistent approach for 23 countries. We include the four missing countries in a sensitivity run in Section 5.

3.3. Matching IO and HH data

So far, we have derived the total emissions associated with the consumption of all households within one country. For an incidence analysis, the impacts for single households need to be derived. To do so, we have to link the MRIO and household data. We match the 57 GTAP 9 sectors with the most disaggregated level of the HBS categories according to conversion tables provided by GTAP and links via ISIC conversion tables where necessary (GTAP, 2021). The most disaggregated HBS level consists of 200 categories. We double-check our matching procedure against the tables in Dorband et al. (2019). In general, as

[3] Czech data does not allow the calculation of aggregate numbers, whereas Swedish data is not disaggregated enough (especially for energy consumption).

Hubacek et al. (2017) point out, three situations can occur when matching household data with MRIO data. First, one expenditure category matches one MRIO category exactly. Second, various expenditure categories correspond to one MRIO category. Third, one expenditure category is linked to two or more MRIO categories. At the 5-digit level of the COICOP-HBS categories, only cases 1 and 2 occur in our matching procedure. In these two cases, the matching is straightforward. In case 1, all emissions from the MRIO data fall in with the respective expenditure category. In case 2, the emissions from one GTAP 9 sector are linked to various expenditure categories. Consequently, these expenditure categories share the same carbon intensity in our model. The emissions assigned to each expenditure category are proportional to that categories expenditure share in overall expenditure associated with the categories that are matched to the same GTAP 9 sector. Table A.1 shows the full matching table. Germany does not provide data at the 5-digit level for some expenditure categories.[4] To obtain the same disaggregated consumption level, we use average German consumption patterns for the estimation of the disaggregated consumption shares within these categories. In the case of Italy, we generated a country-specific matching table because data in the respective subcategories is missing for one 4-digit and one 3-digit-category.

3.4. Microsimulation of the carbon tax burden

To calculate the incidence of a carbon tax on European households, we estimate households' direct and indirect emissions with the environmentally extended MRIO model referred to above. The resulting carbon footprint depends on sectoral carbon emissions, supply chains and household-dependent expenditure patterns. We then simulate the implementation of a carbon tax on all sectors in addition to pre-existing taxes and assume a pass-through rate of 100%. That is, the additional costs stemming from the carbon tax are incurred in their entirety by the households.[5] GTAP 9 only provides data on CO_2 emissions, not on other greenhouse-gas emissions. Consequently, the carbon tax analyzed here is imposed on CO_2 emissions only. In our analysis, we focus on the first-order effect of a carbon tax since our aim is to measure the initial incidence of that tax. No changes occur on the supply or demand side. We relax this assumption in Section 5.

We set the carbon price in our analysis to 25EUR/tCO_2. We assume that this carbon price falls on top of all other existing carbon prices both at the European and at the national scale, thus raising the price in the EU-ETS from roughly 14 EUR/tCO_2 in 2010 to 39 EUR/tCO_2, and equivalent increases of national price levels. This price increase leads to a carbon price level that is in the lower range of carbon-prices consistent with achieving the Paris temperature target (High-Level Commission on Carbon Prices, 2017). However, in light of possible political obstacles (Klenert et al., 2018), this carbon price level can be seen as a reasonable entrance price (see also the discussion in Dorband et al., 2019) to ambitious climate policy that is thus politically relevant. Indeed, the EU-ETS price in 2021 has so far been at around 40 EUR(2010)/tCO_2 (Reuters, 2021). Thus, our impact analysis is a timely contribution to designing carbon pricing and redistribution in the implementation phase of more ambitious policy measures and can be interpreted as the additional effect of increasing the European carbon price from 2010 levels almost to current levels.[6]

In our central scenario, we impose the carbon tax on all sectors and on both locally produced and imported emissions. This scenario mimics increased European ambition in terms of sectoral and global coverage of the carbon pricing scheme. Assuming that national carbon pricing schemes remain unchanged in our scenarios implies that countries with these schemes impose more ambitious carbon pricing schemes than those without national carbon pricing schemes. Differences between European and country ambition have been observed constantly since the implementation of the EU ETS (Worldbank, 2020). For illustrative purposes, we also include two scenarios in which only emissions from the EU ETS sectors are subject to a tax increase (Section 5).

The required steps for the calculation of the carbon footprint of one household and the relative additional burden are as follows. Let the set of households in the HBS be HBS_r^l, where r refers to the country in the set of EU countries and $l \epsilon \{1, \dots, n_r\}$ refers to the corresponding household, where n_r is the total number of households in country r in the HBS. Let the expenditures for item s of the corresponding household be denoted by $hbs_{r,\ s}^{\ l}$, and the total sum of household expenditures in region r on item s according to the HBS be $y_{r,\ s}^{\ HBS}$.[7] Carbon intensities for items are gained by dividing $F_{r1,\ s1}^{\ HH}$ by the total corresponding household expenditures. These intensities are then used to calculate household emissions $emi_r^{\ l}$ as follows: $emi_r^l = \sum_s emi_{r,s}^l = \sum_s hbs_{r,s}^l \bullet \mathrm{F}_{r,s}^{HH} / \mathrm{y}_{r,s}^{HBS}$. The total carbon tax burden for a household results as $b_r^{\ l} = emi_r^{\ l} \bullet p$, where p is the carbon price set to 25 EUR/tCO_2. The relative burden is given by $\Delta b_r^{\ l} = b_r^{\ l} / hbs_r^{\ l}$, where $hbs_r^{\ l} = \sum_s hbs_{r,\ s}^{\ l}$ are the total expenditures of household l in region r. The additional relative burden is thus defined as the additional yearly costs that a household would spend on consumption due to the tax divided by the total expenditures of that household. Note that tax revenues collected in this step are assumed to not be used at all. We use current expenditures as a proxy for lifetime income because it has been convincingly argued that they are a more accurate reflection of a household's economic well-being than current income (see Poterba (1989), Poterba (1991), and Sterner (2012b) for discussion).

4. Results

This section derives the carbon-tax incidence in Europe. Section 4.1 focuses on the case prior to redistribution of tax revenue, analyzing the EU aggregate and the tax burden for 23 EU member states. Section 4.2 introduces different redistribution mechanisms. Section 4.3 discusses the characteristics of households that are especially affected.

4.1. European incidence and its national precursors

Fig. 1 shows the distributional impact of a European carbon tax based on expenditure deciles for the aggregate population of 23 EU states. Each boxplot summarizes the distribution of the relative burden of all households in this expenditure decile. The impact is calculated without recycling the tax revenue collected. The tax is near to neutral for the upper half of the European population. For the lower half of the population, however, we observe a regressive pattern. With a median of 2.6%, the burden for the lowest decile is more than double that of deciles 5 to 10 (roughly 1.1–1.2%). If we look at the interquartile range of each boxplot in each decile (the range between the 25th and the 75th percentile), then the differences between the deciles stand out more starkly. In the lowest two deciles, a carbon tax of 25 EUR/tCO_2 could increase expenditure by more than 4% for around one quarter of households. This number is well below 2% for the expenditure deciles 5 to 10.

One may conjecture that regressivity at the European level reflects

[4] Food and non-alcoholic beverages; alcoholic beverages, tobacco, and narcotics; water supply and miscellaneous services relating to dwellings; transport services. We use average consumption patterns at the 4-digit-level from 2010 and disaggregate it at the 5-digit level with 2015 data: https://www-genesis.destatis.de/genesis/online, Table 61111-0007, (accessed September 28th, 2020).

[5] The empirical evidence in Andersson (2019) confirms that in the Swedish case the carbon tax is passed on fully to consumers.

[6] Please note that the results in our central scenario are linearly scalable in the carbon price level as in Dorband et al. (2019).

[7] In Section 3.3 we explained how we match GTAP sectors and HBS items. Therefore, the indicator s refers to the common categories after the matching procedure. Please see the Table A1.

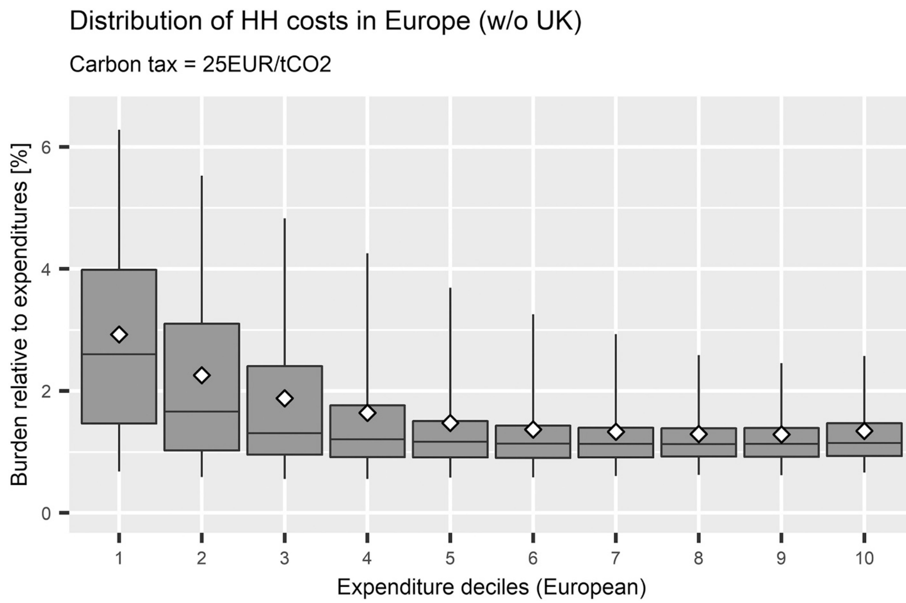

Fig. 1. Carbon-tax burden prior to redistribution based on European expenditure deciles. Outliers are excluded. The black line marks the median value per decile; the white rectangle the mean. The grey box represents the range of the 25th to the 75th percentile (interquartile range). The whisker below (above) the grey box ends at the 5th (95th) percentile.

regressivity of the tax within some EU member states. However, Fig. 2 reveals that EU regressivity is driven by differences in average characteristics between EU countries rather than within-country differences. We disentangle these effects via decomposing the relative tax burden of a household i in decile j of country r (Δb_{rji}) into four components: the EU average relative tax burden, the between-country contribution, the within-country contribution and the horizontal contribution:

$$\Delta b_{rji} = \underbrace{\Delta b_{EU}}_{EU\,average\,burden} + \underbrace{(\Delta b_r - \Delta b_{EU})}_{Between-country\,contribution} + \underbrace{(\Delta b_{rj} - \Delta b_r)}_{Within-country\,contribution} + \underbrace{\Delta b_{rji} - \Delta b_{rj}}_{horizontal\,contribution}$$

The between-country contribution is the difference between the national average of the carbon tax burden (Δb_r) compared to the EU average (Δb_{EU}). It shows how EU countries differ among each other. The within-country contribution is the difference between the average tax burden of deciles at the national level (Δb_{rj}) to the national average. It shows the vertical inequality of the carbon tax within countries. The horizontal contribution is the difference between the household's individual relative burden and the average relative tax burden of the decile at the national level. It captures the horizontal inequality within national expenditure deciles.

Fig. 2 plots this decomposition as the distribution of the three contributions per European expenditure decile. The sum of the three components in Fig. 2 plus the average EU tax burden would yield Fig. 1. The between-country effect is clearly regressive until decile five and proportional from decile 6 to 10. The within-country effect, however, follows a slightly progressive pattern, especially notable from decile 1 to 4, whereas the horizontal effect is proportional on average.[8] We conclude that the between-country effect is the essential driver of European regressivity and not the within-country or horizontal effect.

Appendix B provides further evidence for our main result. A regression analysis confirms that between-country differences drive regressivity at the EU-level. The analysis shows that while EU households with lower expenditure on average experience a higher relative carbon tax burden (the finding of Fig. 1), this effect disappears once country-level dummies are introduced (the finding of Fig. 2). The results are robust to including a possible rural vs urban divide. On average, households living in sparsely populated areas have a higher relative carbon tax burden. However, country-level characteristics remain the strongest driver behind a household's relative tax burden.

4.1.1. National characteristics that drive the European incidence

Two characteristics are the main contributors to the regressive between-country pattern. First, households from countries with lower average expenditure populate lower-expenditure deciles at the EU level. Citizens from Bulgaria, Poland, and Romania mainly populate the lowest expenditure decile. Fig. 3 clearly illustrates this. The dominance of inter-country differences is so large that hardly any households from these three countries are to be found in the highest (European) decile.

Second, these three countries have an average tax burden for CO_2 emissions that is much higher than in most other countries, as shown in Fig. 4a and Fig. A.1 in the appendix. The median carbon tax burden is roughly 4.3% in Bulgaria and 3.8% in Poland across all national deciles. Romania is not far behind. By contrast, consumers in the countries that make up the highest European decile - Germany, France, and Italy - pay an average tax of less than 1.4% across all deciles.

A closer look at the shape of the national impacts reinforces the point concerning intra- and inter-country comparisons. The corresponding diagram for France and Italy shows that the corresponding curves are slightly progressive (see Fig. 4a). Overall, the national distribution of burdens is mostly either proportional or slightly progressive (see Fig. A.1). The differences between the impacts for the deciles are rather small. In some of the low-income countries, we observe a tendency for the tax to be progressive (e.g. Poland, Romania, and Hungary). Some countries do not fit into this pattern. Luxembourg, for example, overall shows a regressive impact. In some countries, a tax may be neither progressive nor regressive if, for example, the deciles in the middle pay most (Greece and Cyprus). These variations demonstrate that also other factors influence the distribution of the tax burden locally, such as

[8] Note that the results for the within-country and the horizontal contribution also include re-ranking effects between national and European expenditure deciles; i.e. two households from the same national decile can end up in different European deciles. The horizontal contribution at the national scale would be by definition proportional on average. The horizontal contribution at the European scale can, however, be influenced by re-ranking. The panel for the horizontal contribution in Figure 2 shows that re-ranking does not change the proportional pattern notably.

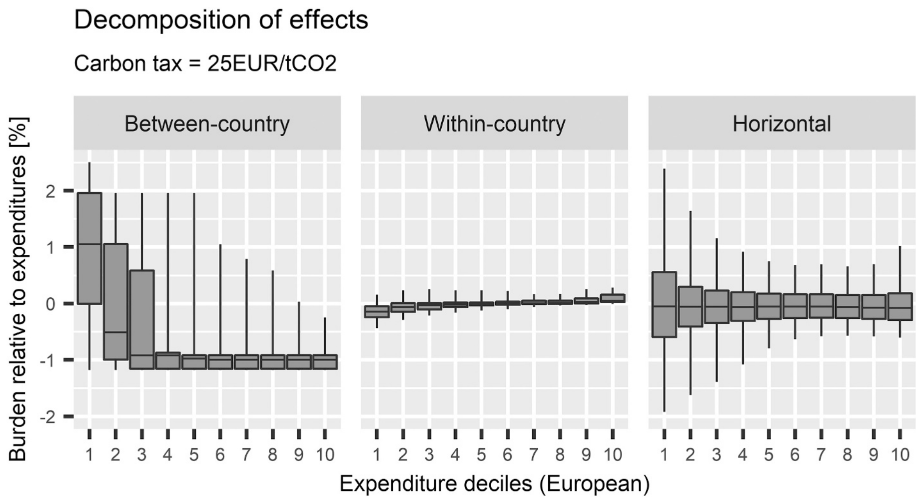

Fig. 2. Carbon-tax burden decomposed into three dimensions: between, within and horizontal. The carbon-tax burden is prior to redistribution and based on European expenditure deciles. Outliers are excluded. The black line marks the median value per decile. The grey box represents the range of the 25th to the 75th percentile (interquartile range). The whisker below (above) the grey box ends at the 5th (95th) percentile.

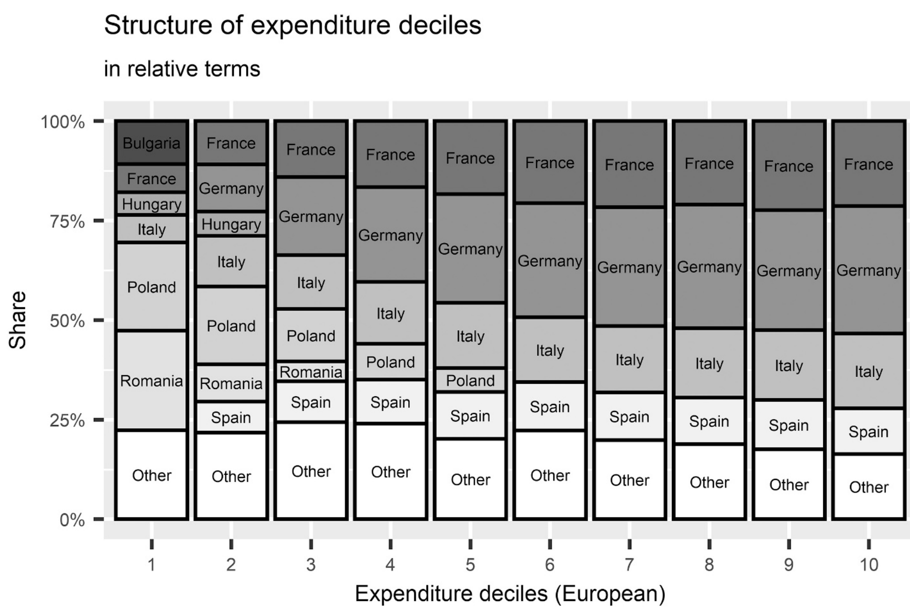

Fig. 3. Population shares of EU expenditure deciles from each EU country. Countries with a share of below 5% in a decile are summarized in the category "Other". Bulgaria, for example, has a share of 10.8% in decile 1 and a share of 3.7% in decile 2. Table A.2 reports shares of all countries.

population density, availability of public transport, and climate.[9]

Comprehensive carbon pricing of all goods and services drives neutral to progressive impacts of the tax within EU countries. To see this, Fig. 4b shows the relative tax burden originating from electricity, direct and indirect emission consumption within six selected EU member states. Previous literature indicates that, especially in developing countries, taxes on fuels are generally less regressive than those on energy consumption for heating and on electricity (De Mooij et al., 2012). In fact, taxes on motor fuels are typically progressive in developing economies (Peters, 2012; Sterner, 2012b; Labeaga et al., 2020). Fig. 4b confirms these findings. A tax specifically and only on electricity would tend to be regressive. This applies to all countries, but the effect is particularly marked in low-income countries such as Bulgaria or Romania. The obvious interpretation is that electricity is used for universal necessities such as cooking and lighting, but the tendency to increase consumption with rising income is weak. The results in Brännlund and Vesterbert (2018) confirm it for Sweden.

By contrast, Fig. 4b also shows results for direct fossil-fuel use and indirect carbon use. The latter has a striking tendency to increase with income. If the EU had a more complete system of carbon pricing, a larger share of final goods would embed their total carbon content in the price, and the burden would fall on the consumers of those goods. A relatively higher share of this burden from indirect emissions would fall on the high-income earners.

This also provides a stark contrast to the final category shown in the figure, that of direct emissions. Here our results are close to those in Sterner (2012a, 2012b). In low-income countries, the impact is progressive. In the more affluent EU countries, a tax on these direct emissions would tend to be broadly neutral. There is a slight tendency for

[9] We could not further identify main drivers behind incidences that diverge from progressivity or neutrality and leave a more thorough analysis for future research.

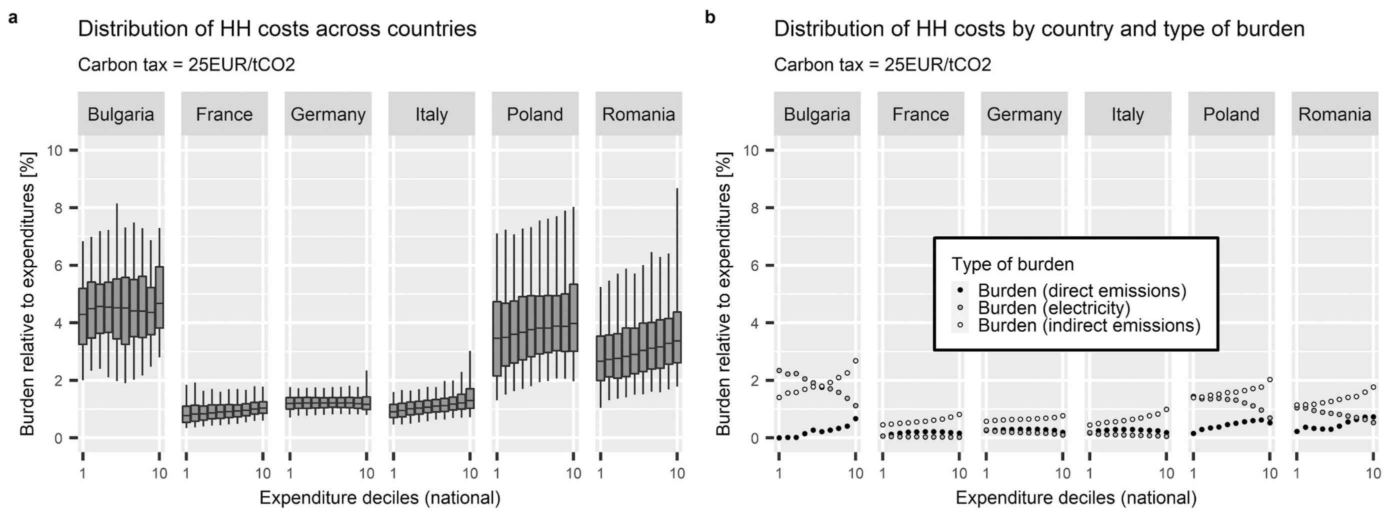

Fig. 4. National carbon-tax burden for selected EU countries (see Fig. A.1 for all 23 EU countries). (a) Carbon-tax burden prior to redistribution based on national expenditure deciles (median, interquartile range, and 5 to 95% range); (b), Median tax burden split into three components. Direct emissions (coal, petroleum, and gas), emissions from the national electricity sector, and indirect emissions (embodied in the production process of purchased household goods). Outliers are excluded.

regressivity to make itself felt in parts of the income spectrum in countries such as France, Italy, and (less clearly) Germany, where the graphs for the direct burden have an inverted-U shape. This suggests that the most affected are households in the middle segment of the income distribution.

4.1.2. Sectoral contribution to regressivity at the European scale

The regressive impact of carbon taxation on the European level is driven by between-country differences. To identify drivers why low-income countries have a higher carbon tax burden than high-income countries, we next decompose the contribution of each country to the regressive pattern based on different sectors of the economy. Fig. 5 displays the three sectors that contribute the most to the tax burden

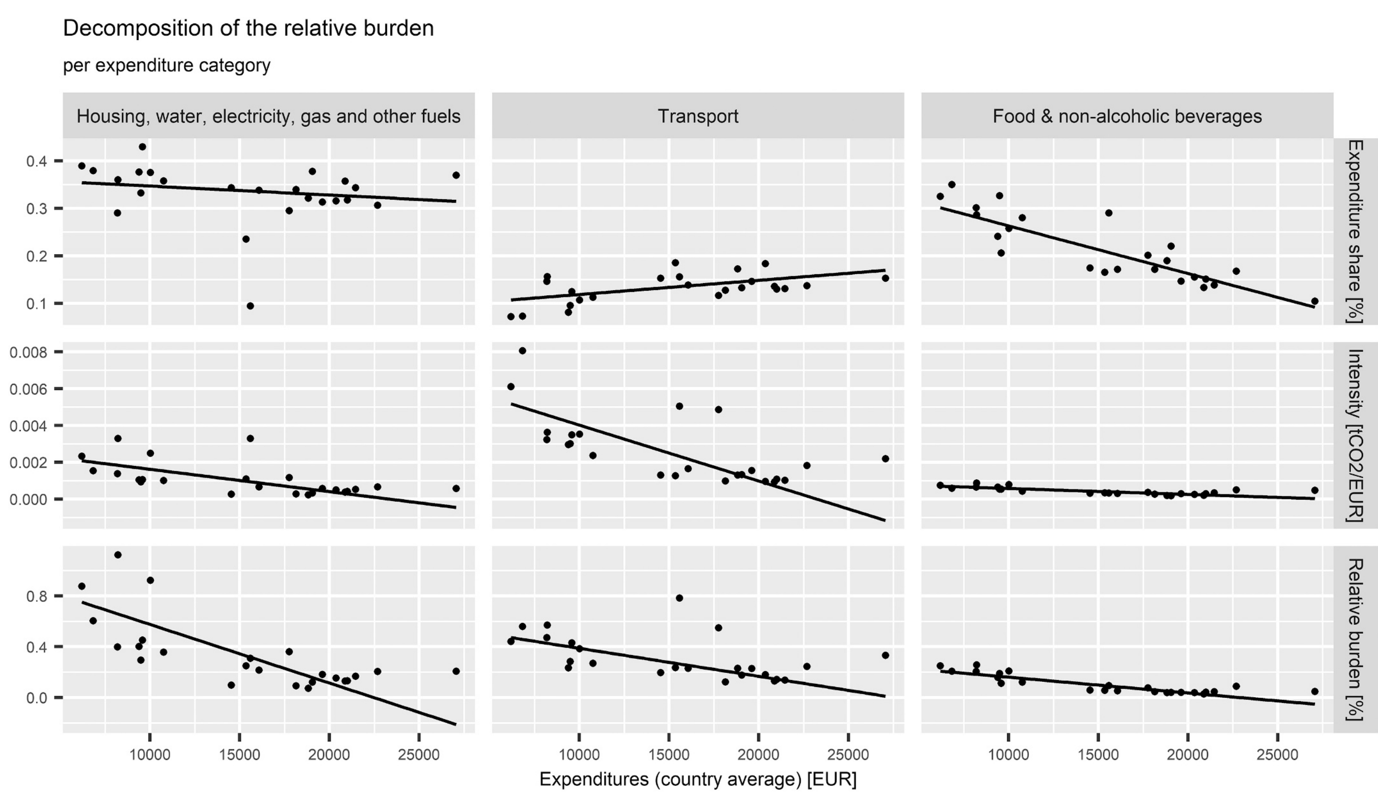

Fig. 5. Each country's contribution to European carbon tax impact by economic sector. The three sectors shown are "Housing, water, electricity, gas and other fuels", "Transport" and "Food and non-alcoholic beverages" (Figure A.2 in the appendix shows all 12 COICOP sectors). Three national indicators are plotted against each country's average expenditure. The first row shows the average household expenditure share of the respective sector, the second the carbon intensity in each sector, the third the average carbon tax burden originating from each sector. The tax burden depicted in the last row is the product of the values of the two other rows. The line in each plot represents the linear fit to guide the eye.

Table 1
Description of indicators for redistribution.

Scenario	National equal-per-capita	European equal-per-capita	Targeted transfers	High-intensity consumers
Description	National tax revenue is recycled with equal transfer per person in the country	European tax revenue is recycled with equal transfer per person in every country	All households in deciles 1–4 receive the same cash transfer that equalizes the median burden of the first and the fifth decile	Share of households that have a higher tax burden than one standard deviation above the mean of the entire distribution of burdens in the EU
Revenue recycled	100%	100%	6.6%	Unspecified

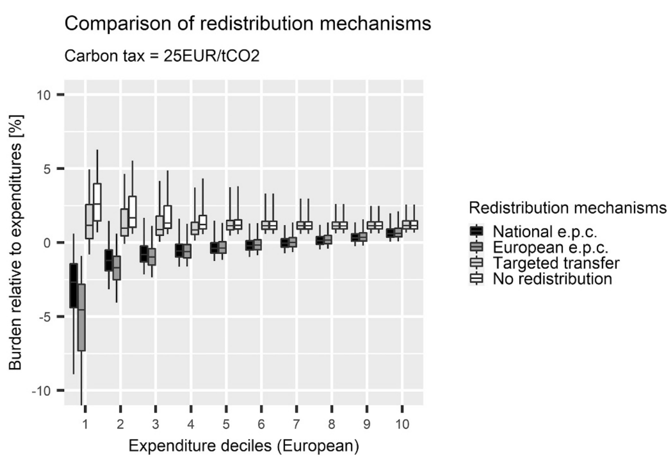

Fig. 6. European carbon-tax incidence under different redistribution mechanisms. 1. A national equal-per-capita redistribution of a national carbon tax revenue (in black); 2. a European equal-per-capita redistribution of a European carbon tax revenue (dark grey); 3. an equal-per-household redistribution for deciles 1 to 4 only that equalizes the median incidence in decile 1 to that of decile 5 (light grey). Note that the fourth case (white) is the incidence of the tax without refunding (reproducing Figure 1), where the revenue raised has not been returned to the economy and all deciles are negatively affected. Similarly, the Targeted program (light grey) also leaves tax revenue that is not refunded. Outliers are excluded.

compared to all sectors: Housing, transport, and food (Fig. A.2 in the appendix shows the contributions of all 12 COICOP sectors with a description of how we calculate the factors). Fig. 5 plots each country's average burden that originates from the respective sector against the country's average expenditure (third row). It also shows the two factors determining the average burden: the average expenditure share (first row) and the average carbon intensity (second row) of this sector. The product of these two factors gives the average burden.

All three sectors contribute to the regressive impact on the European scale: those countries with the lowest expenditures are the ones with the highest relative burden. In particular, the housing sector's contribution to the regressive pattern is high for expenditures below 15,000 Euros. The two factors make up the regressive between-country pattern of the burden. First, low-income countries spend on average a larger share of their income on housing. Second, the carbon intensity of the housing sector is slightly higher in low-income countries. The transport sector also contributes to the regressive European incidence: the relative tax burden decreases as national expenditure rises. Here, we however observe that the expenditure share increases with rising expenditures. The difference in carbon intensities turns the relative tax burden regressive for transport even though the expenditure share increases with national expenditures: the transport sector has a higher carbon intensity in low-income countries. In the food sector, the pattern is reversed. While the carbon intensity is very similar across all European countries, the expenditure share in the food sector drives the regressive contribution to the European carbon tax impact. Overall, a regressive pattern from the food sector emerges.

Table 2
Share of total transfer allocated to the different EU countries under (1) National equal per capita (2) European equal per capita (3) Targeted transfers (4) High-intensity consumer share (5) EC's Just Transition Fund. The first row shows the total amount transferred. The second row shows that Belgium would get 3.7% with national refunding and 2.7% with EU-wide refunding. The first figure is larger because Belgium has higher than average emission consumption and thus tax revenue. Belgium would receive 1.4% with Targeted transfers, since there are fewer households in the lowest four EU deciles. The next column shows a very low share of high-intensity consumers (0.01%) because Belgium has only very few candidates in the "most affected" category (see Section 4.3 for details). Finally, the last column shows what Belgium would get from the proposed EU Just Transition Fund.

Member state	1 National EPC refund	2 European EPC refund	3 Targeted transfers to deciles 1–4	4 High-intensity consumers	5 Just Transition Fund
Total transfer	57.5 B EUR	57.5 B EUR	3.8 B EUR	unspecified	17.5 B EUR
Belgium	3.7%	2.7%	1.4%	0.01%	0.9%
Bulgaria	1.1%	1.9%	4.4%	11.4%	6.1%
Croatia	0.7%	1.1%	1.6%	0.6%	0.9%
Cyprus	0.4%	0.2%	0.1%	0.1%	0.5%
Denmark	1.8%	1.4%	0.7%	0.0%	0.5%
Estonia	0.4%	0.3%	0.8%	2.0%	1.7%
Finland	1.8%	1.4%	1.1%	0.04%	2.2%
France	15.4%	16.4%	12.1%	0.7%	5.4%
Germany	24.6%	20.6%	14.2%	0.02%	11.7%
Greece	5.9%	2.8%	2.4%	8.2%	3.9%
Hungary	1.7%	2.5%	4.9%	5.0%	1.2%
Ireland	1.4%	1.2%	0.6%	0.1%	0.4%
Italy	15.7%	15.0%	12.2%	1.4%	4.9%
Latvia	0.4%	0.5%	1.1%	1.4%	0.9%
Lithuania	0.5%	0.8%	1.5%	0.7%	1.3%
Luxembourg	0.4%	0.1%	0.03%	0.1%	0.05%
Malta	0.2%	0.1%	0.1%	0.3%	0.1%
Poland	8.9%	9.6%	16.0%	47.1%	26.7%
Portugal	1.9%	2.7%	3.3%	0.1%	1.1%
Romania	2.5%	5.1%	10.5%	18.7%	10.1%
Slovakia	1.0%	1.4%	2.4%	1.9%	2.2%
Slovenia	0.5%	0.5%	0.5%	0.02%	1.2%
Spain	9.1%	11.8%	8.3%	0.05%	4.1%
Austria	–	–	–	–	0.7%
Czech Rep.	–	–	–	–	7.7%
Netherlands	–	–	–	–	2.9%
Sweden	–	–	–	–	0.8%
Total	100%	100%	100%	100%	100%

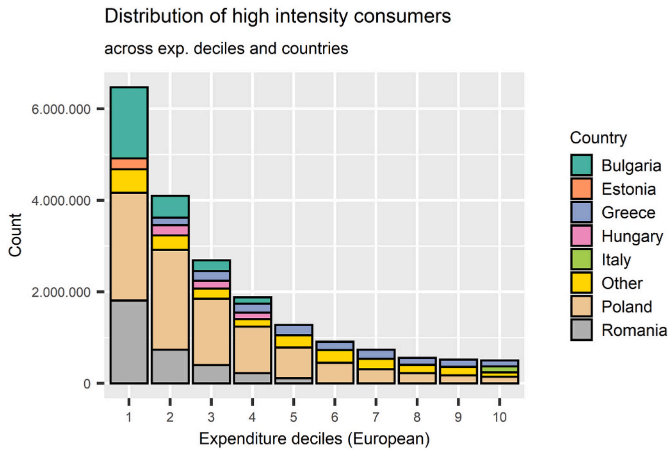

Fig. 7. Distribution of high-intensity consumers across European deciles. High-intensity cases are defined as having a burden above one standard deviation from the entire European distribution. Countries with a relative share below 3 % and an absolute number of below 100.000 per decile are summarized in "Other". (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Alleviating the carbon tax burden: indicators for redistribution

The European carbon tax displays a regressive pattern for the lowest income groups. As we have shown this is largely caused by between-country differences and driven by relatively high carbon tax burden in low-income member states. Revenue redistribution could alleviate the tax burden and influence the outcome for poorer households. However, we need to be cognizant of the fact that the nation states of the EU are sovereign and that the mechanisms for distribution between them are limited; for reasons that are legal, constitutional and political. As illustrated by the Green Deal and the Just Transition Fund, the European ambition for redistribution has increased. To assess various policy options, we consider four different indicators for redistribution that are summarized in Table 1.

We simulate two redistribution schemes with equal-per-capita mechanisms (EPC). In the first scheme, the national carbon tax revenue is recycled to households within each country on an EPC basis. Persons in each country receive the same transfer, but the transfer differs between countries. In the second scheme, the total European tax revenue is recycled EPC. Each person in the EU receives the same cash transfer. The third policy option, Targeted transfers, is implemented on an equal-per-household basis to directly offset the tax incidence of EU households. The cash transfer equalizes the median incidence of the lowest decile to that of the fifth decile. Under the Targeted transfers scheme, all households in deciles 1 to 4 receive the same cash transfer, while the higher deciles receive no transfer. Fig. 6 shows the distributional impact of these three options. Lastly, we consider an indicator for redistribution that targets especially affected households. Households are identified as high-intensity consumers if their carbon tax burden is higher than the carbon tax burden at one standard deviation above the mean of all European households (3.1%). The indicator for redistribution computes the share of high-intensity consumers in each European country.

We compare each redistribution indicator to the allocation of resources from the Just Transition Fund that is part of the Green Deal (EC, 2020). The Just Transition Fund is currently scheduled to redistribute 17.5 billion EUR across the EU countries. The funds are allocated to regions and sectors most seriously affected by more ambitious climate policy (EC, 2021a).

4.2.1. National equal per capita transfers

National EPC refunding of taxes, the first case, has often been discussed in the literature (Carattini et al., 2017; Nature Editorial, 2017; Klenert et al., 2018). The transfers reveal significant variations between countries, as they will collect very different amounts of revenue with the same tax. The lowest average tax revenue and thus per-capita redistribution is found in Romania (72 EUR), the highest per-capita redistribution in Luxembourg (462 EUR). Table 2 reports the share of the total European tax revenue allocated to each country under the National EPC scheme. As shown by the black bars in Fig. 6, this mechanism is able to reverse the regressivity of the tax burden. Most people are better off after such a tax reform, but note that especially the 10th decile is a net loser on average. Furthermore, we still have a source of inequity between countries because on average households in lower-income countries like Poland and Romania are more seriously affected (see Fig. 4a). This clearly shows the limits of what national refunding can achieve in low-income countries.

4.2.2. European equal per capita transfers

National refunding schemes miss the main driver behind the regressivity of the European carbon tax: inter-country differences. An alternative in line with a European Green Deal might be an EPC implemented at the European level, the second case. Here, the entire carbon tax revenue from all member states would be redistributed on a European EPC basis. The transfer amounts to 145 EUR per capita, which is comparable to individual country transfers in Slovenia in case of the national EPC. For low-income countries like Romania, the per-capita refund would be roughly doubled. Table 2 again reports the share of total tax revenue allocated to each country under the European EPC. The dark grey bars in Fig. 6 show that under the European EPC very poor EU households would benefit to a larger extent from this refunding model. The outcomes imply that countries with a higher average burden (see Fig. 4a) receive transfers from more affluent countries with lower average burdens, making total incidence more progressive after redistribution.

4.2.3. Targeted transfers

Implementing the EPC redistribution schemes above may however not be desirable, as the entire tax revenue is used in refunds, which, in our example, is *more than enough* to offset the burdens on most households. Part of the revenues may also be allocated to green investment activities to spur the transition to a low-carbon economy. This is, for example, also part of the EC's Green Deal proposal (EC, 2021a). Accordingly, in Fig. 6, we consider an additional mechanism that uses only a small share of the revenues but targets them at households that are especially affected (depicted in light grey). This mechanism equalizes the median incidence of the lowest decile (2.6%) to the median of the fifth decile (1.2%). Households in deciles 1 to 4 each receive the same cash transfer (57.5 EUR per household), which is the minimum required to achieve proportional burden at the median on a European level. Only 3.8 billion EUR are needed to achieve proportionality. Table 2 reports the share of the 3.8 billion that is allocated to each country under the Targeted transfer scenario. Note that we set the transfer to deciles 5 to 10 at zero, as the median incidence is nearly the same for these deciles. Deciles 1 to 4 vary in their incidence, as cash transfer is the same for all of them.

4.2.4. High-intensity consumers

All three redistribution schemes in Fig. 6 only alleviate the burden on the median of households for each decile. However, there are households who are subject to a higher incidence, as can be seen by the upper whiskers in each decile in Fig. 6. Accordingly, we now consider households with a particularly high burden as an additional indicator for redistribution (higher than the burden at one standard deviation above the mean of the entire distribution of burdens in the EU, roughly 3.1%). Table 2 reports the share of high-intensity consumers found in each EU country. It shows that it is mainly Eastern European countries with a significant share. Most high-intensity consumers are located in Bulgaria, Poland, and Romania, with a total share of over 75% of all cases. We further identify the properties of high-intensity consumers in Section 4.3.

4.2.5. Comparison of redistribution indicators and the Just Transition Fund

Table 2 shows the share of the total European tax revenue (57.5 billion EUR) allocated to each country for the two EPC mechanisms. In the second column, each country "keeps" the taxes paid by its citizens and refunds them on a national EPC basis. This would be the result if the EU were to agree on a common (but nationally implemented) tax in each member country. In column three, the European total is refunded on a European EPC basis, which generally implies higher (lower) refunds for citizens in low-income (high-income) countries. Note that the figures in column 2 are proportional to each country's emissions - including imported ones. These figures represent each country's share in the total European tax revenues collected. The figures in column 3 are proportional to each country's population. One can see that over and against national EPC, mainly northern and western European countries (Belgium, Germany, Ireland etc.) are net donors under the European EPC mechanism, with eastern European countries being net recipients. Hence, European EPC is able to reflect some of the inter-country differences that cause regressive incidence.

In comparison, the Targeted transfer scheme indirectly targets low-income countries within the EU to a larger extent than European EPC because the lowest four deciles are money recipients and countries are not equally represented in these deciles (see Fig. 3). Column 4 of Table 2 shows the share of revenue allocated to each EU country under the Targeted transfer scheme. Since refunds are only given to households in the lowest four deciles, redistribution is highly targeted. With its much lower cash transfer per household, Targeted transfer is, however, limited in the extent to which it reaches households with above-median incidence. The advantage is that it uses only 3.8 of the 57.5 billion EUR collected (6.6%) and is still able to mitigate regressivity at the median and make the incidence neutral-to-progressive in Fig. 6.

The share of high-intensity consumers indicates even more skewed redistribution across the EU, column 5 of Table 2. Almost half of all high-intensity consumers are located in Poland, with most found in eastern European countries. Using part of the tax revenue according to this indicator would compensate especially affected households, thus a skewed redistribution to more carbon-intense and lower-income countries should be implemented.

Comparing the indicators in Table 2, both the Targeted-transfer and the high-intensity-consumer indicators suggest that a large share of total compensation should be allocated to Bulgaria, Poland, and Romania, in comparison to the EPC transfers. Interestingly, the simple average of the Targeted transfer and the share of high-intensity consumers is fairly close to the share specified by the EC for the Just Transition Fund. Eastern European countries receive a higher share than the share they generate in revenue (equal to the national EPC in column 2). For example, when we combine the Targeted-transfer and the high-intensity-consumer shares with equal weights, the average is a share of 7.9% for Bulgaria, 7.1% for Germany, 6.4% for France, and 31.6% for Poland. The Just Transition Fund allocates 6.1% to Bulgaria, 11.7% to Germany, 5.4% to France, and 26.7% to Poland. The similarity is no coincidence, as the allocation rule of the Just Transition Fund is based largely on above-average emission intensities in European regions and on gross national income. Exceptions are Hungary, Latvia, and Romania, where both indicators in columns 4 and 5 of Table 2 point to a higher share of resources allocated to households in these countries than in the Just Transition Fund proposal.

In conclusion, we argue that the indicators 'Targeted transfers' (column 4) and 'high-intensity consumers' (column 5) in Table 2 are relevant for European redistribution when designing climate policy. More specifically, it could be explicitly included in the Just Transition Fund along with the indicators already in place. It would help increase the visibility of implementing a just transition with the Green Deal, thereby improving the political acceptability of the policy. Distributional fairness and revenue salience are among the most important factors in successfully implementing carbon pricing. Targeted and equal per capita transfers are promising redistribution mechanisms for the purpose (Klenert et al., 2018). However, it might also be necessary to take into account country-specific characteristics (Stiglitz, 2019) and other factors than the distributional impact of the carbon policy (Douenne and Fabre, 2020). A clear communication strategy of the environmental, economic, and societal costs and benefits of the carbon policy can increase public and political support (Carattini et al., 2018). The results summarized in Table 2 can be drawn upon to communicate that the EC is taking due account of the way its citizens are initially affected by higher carbon prices.

4.3. Properties of high-intensity consumers

High-intensity consumers face a large burden from the carbon tax. Without targeted compensation, climate policy may severely increase inequality, thus endangering the successful implementation of the tax from a broader societal perspective. In this section, we further investigate the characteristics of high-intensity consumers to identify them within the European distribution.

We first examine in how far high-intensity consumers can be identified from their expenditure. Fig. 7 shows where high-intensity consumers are to be found along the European expenditure distribution. We find that these are predominantly located in the lowest expenditure deciles. Almost 70% of the high-intensity cases are to be found in the three lowest deciles. There are only a few high-intensity consumers in the highest deciles (less than 3% of all high-intensity consumers). For the poorest households, high-intensity consumption means that the carbon tax will hit these households very hard. Accordingly, we define them as "hardship cases". Introducing the tax will place a large burden on these households that they will probably find difficult to compensate for. Most hardship cases are located in Bulgaria, Poland, and Romania, their share of all high-intensity cases is over 75%. Compensation based on the share of high-intensity consumers would focus on Bulgaria, Estonia, Poland and Romania as their share thereof is large compared to their population share (compare column 5 in Table 2 to column 3, which is the share of population in each EU country). These four countries have similarities like the high electricity carbon intensity in Estonia and Poland (see Ward et al., 2019) and the high overall energy intensity (see Eurostat, 2021).

Next to expenditure, a plausible conjecture is that the large carbon tax burden is due to divide between rural and urban areas.[10] Fig. 8 shows the distribution of high-intensity consumers split according to their area's population density. We find that in the lowest decile, high-intensity consumers are more prominently located in sparsely populated areas. The figure is more than 2 times higher than in densely populated areas. The ratio however is reversed in the higher deciles. From Fig. 8 we learn two things: It is necessary (i) to not only

[10] We follow the Eurostat definition and its three categories: Densely Populated (at least 500 inhabitants/km2), Intermediate (between 100 and 499 inhabitants/km2) and Sparsely Populated (less than 100 inhabitants/km2).

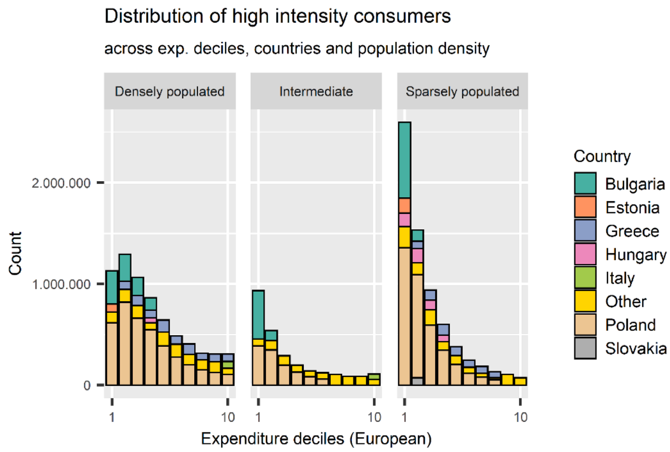

Fig. 8. Distribution of high-intensity consumers across densely and sparsely populated areas. No information on this was available for Romania. Countries with a relative share below 3 % and an absolute number of below 50.000 per decile and density level are summarized in the group "Other". (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

compensate households in rural areas, as many high-intensity consumers with low expenditure are to be found in densely populated areas, and (ii) to specifically compensate lowest-expenditure European households located in rural areas, as these represent the largest number of high-intensity cases.

Additionally, we checked whether we can identify high-intensity consumers on the basis of their expenditure patterns. The results in Fig. A.3 show no clear indication that high-intensity consumers have a particularly high burden from, say, the direct consumption of fuels or from electricity, so we discard the hypothesis.

Overall, high-intensity consumers are mainly characterized by low expenditures rather than a potential rural/urban divide or specific consumption patterns. Our analysis is however limited due to data availability. Future research should investigate in more detail how to identify high-intensity and especially hardship cases to design appropriate compensation.

5. Technical discussion

We now discuss how our main modeling assumptions influence our central result that the EU carbon tax is regressive prior to revenue recycling (see Kosonen, 2013 and Ohlendorf et al., 2021 for a detailed review of the literature on which factors influence the distributional effects of climate policy). We provide further analyses that relax some of these assumptions, all of which confirm our central estimate. These scenarios are the following: including demand-side responses; changing the regional and sectoral coverage of the carbon tax, correcting for household under-reporting; adding the UK to EU climate policy; adding the four missing EU countries; using income rather than expenditure as our welfare measure. We discuss the conducted sensitivity analyses briefly below. Please see the Appendix C to this article for more detailed information. Table 3 shows the relative burden from the carbon tax per decile and the corresponding Suits Index for the conducted scenarios. The Suits Index is a summary statistics of the distributional incidence of a tax based on the concept of the Gini Index with values ranging from −1 to +1 (Suits, 1977). A negative (positive) Suits index means that the overall impact of the policy is regressive (progressive), with a lower (higher) value indicating more inequality of the tax burden across the expenditure distribution.

We abstract from any changes in demand to derive our central estimate. To relax this assumption, we build a stylized model with demand-side responses assuming different price elasticities considering final prices paid by consumers across sectors and countries based on the literature. We allow for demand-side changes in sectors where the carbon price yields notable price changes and adjust demand according to elasticity estimates from a literature review. Demand-side adjustments are more pronounced if the tax leads to a notable price increase (see Banks et al., 1996). Empirical evidence about price effects reported by Labandeira et al. (2017) shows very low uncompensated and compensated elasticities (and low dispersion) for electricity, natural gas or car fuels, either gasoline or diesel. This is true both for developed countries and the short run, although even in the long run almost all goods in most countries appear as inelastic to prices. However, we also construct a scenario with a relatively high elasticity estimate to derive a lower bound for the additional burden of the tax after demand-side adjustments. This scenario also builds on the findings from Andersson (2019), providing evidence for the fact that the carbon tax elasticity of gasoline demand is significantly larger than its price elasticity. Including demand side responses based on the elasticities reported in Table A.3, the adjusted model results in slightly decreased carbon tax burdens across households but the changes in the regressive pattern are small (see scenarios 2 to 4 in Table 3). We thus conclude that the carbon tax is likely to remain regressive in the short- to medium run. Sager (2019a) finds a more pronounced decrease in the carbon tax burden when taking into account demand- and supply-side changes but still finds a clearly regressive pattern at the global scale.

Table 3
Median relative burden from the carbon tax per decile and Suits Index for the 11 scenarios.

Scenario	Decile										Suits
	1	2	3	4	5	6	7	8	9	10	
1 - Baseline	2.60	1.66	1.31	1.21	1.17	1.14	1.13	1.13	1.13	1.15	−0.104
2 - Demand side - Eastern countries w. high elasticity	2.55	1.64	1.30	1.20	1.16	1.13	1.13	1.12	1.12	1.14	−0.102
3 - Demand side - Eastern countries w. low elasticity	2.57	1.64	1.29	1.19	1.15	1.12	1.12	1.12	1.12	1.13	−0.105
4 - Demand side - equal max. elasticity	2.14	1.51	1.23	1.14	1.10	1.08	1.08	1.07	1.08	1.09	−0.084
5 - EU carbon pricing only	2.16	1.30	1.01	0.91	0.87	0.84	0.83	0.81	0.80	0.79	−0.150
6 - EU ETS carbon pricing only	1.20	0.64	0.46	0.40	0.36	0.34	0.33	0.32	0.31	0.31	−0.219
7 - Underreporting (Eurostat)	1.89	1.31	1.09	1.01	0.97	0.93	0.92	0.92	0.92	0.92	−0.080
8 - Underreporting (GTAP)	2.83	2.72	2.45	2.27	2.15	2.06	2.00	1.97	1.88	1.76	−0.161
9 - with UK	2.47	1.77	1.42	1.29	1.23	1.19	1.18	1.17	1.16	1.18	−0.073
10 - EU 27	3.24	1.87	1.31	1.20	1.16	1.13	1.15	1.22	1.18	1.22	−0.089
11 - Temporary income	4.16	2.78	1.86	1.51	1.34	1.21	1.11	1.03	0.95	0.78	−0.240

The central scenario analyses a carbon price on all sectors and all imported goods. However, a sectoral extension of the EU ETS and border carbon adjustments are still under debate (EC, 2019). To represent the case without border carbon adjustments, we build a scenario where only domestic EU emissions are taxed. In addition, we check the distributional impact if only the EU-ETS price increases (i.e. a scenario without border carbon adjustments and sectoral expansion), a scenario that comes close to the current EU climate policy. Table 3 shows that the overall tax burden decreases notably under scenarios 5 and 6 (more pronounced in the EU ETS only scenario), but the regressive pattern increases as the Suits index shows. It follows that a sectoral extension of the EU ETS to all sectors would have a progressive impact. The same holds for the overall effect of border carbon adjustments on all sectors.

Our main model does not correct for under-reporting. Household budget surveys usually face the problem of under-reporting of expenditures, that is, households report lower expenditures on certain sectors or overall than the true level (Ivanova et al., 2017). We correct for the bias occurring at the aggregate level by relying on national accounts of aggregate expenditure from EUROSTAT and GTAP 9 in two sensitivity tests (see Table A.4). Both tests lead to a regressive distributional impact of the carbon tax across EU deciles, to a lesser extent when using EUROSTAT expenditures and to a larger extent when using GTAP 9 expenditures compared to our central estimate (see scenario 7 and 8 in Table 3).

The UK's future role in European climate policy is still under debate. Therefore, we exclude the UK in our central scenario. However, even with the UK leaving the EU, there is the possibility of future collaboration in the field of climate policy. We thus take into account this possibility and model the distributional impact of a carbon tax on the 23 countries plus the UK. The results confirm the regressive pattern observed in our central scenario (Table 3, scenario 9).

Due to data issues, Austria, the Netherlands,[11] the Czech Republic[12] and Sweden[13] are not part of our central scenario, even though they belong to the EU. In a sensitivity run, we use EUROSTAT's dataset on expenditures by income quintile to include these countries. Table 3, scenario 10, shows that the regressive impact of the carbon tax is still present.

Finally, our concept of welfare also has important implications. Many studies of the carbon tax incidence are based on income rather than expenditure. Since Poterba (1989) suggested that expenditure is a better measure for welfare than income, studies have frequently found that the carbon tax incidence is much more regressive when the welfare measure is income compared to expenditure (Hassett et al., 2009; Cronin et al., 2019; Douenne, 2020). Therefore, in another sensitivity run, we calculate the carbon tax burden relative to current income levels and construct European deciles according to current income.[14] As Table 3, scenario 11, shows, using this welfare measure produces significantly higher burden at the median for lower income households. The opposite is true for high-income households. Thus, this measure of welfare tends to increase the regressivity of the carbon tax. The increased Suits Index confirms this. Note that Italy and Luxembourg are excluded from this scenario because the two countries do not provide data on income in the HBS 2010.

Beyond the demand side response that we analyzed above, there are more general equilibrium impacts for instance due to technical progress or alternative long-run factors affecting substitution of technologies (heating, cooking or lighting appliances or vehicles), for instance (see again Labandeira et al., 2017). In this sense, our results may be biased due to the absence of dynamics in the supply side. Literature that uses general equilibrium modeling generally observes that the incidence becomes more progressive when changes in factor prices, incomes and other general equilibrium effects are taken into account (Rausch et al., 2011; Dissou and Siddiqui, 2014). While we do not explicitly model this, we thus conjecture that our static model tends to be more regressive by abstracting from general equilibrium effects. In addition, analyzing mid- to long-term effects would make it necessary to take into account the influence of the Environmental Engel curve (Sager, 2019b), focusing on CO_2 demand changes when income and income inequality changes. On the other hand, Andersson and Atkinson (2020) show that the carbon tax has become more regressive over time in Sweden, probably caused by an increase in income inequality. Future work should model these additional dynamic effects.

Overall, there is no conclusion whether we over- or underestimate regressivity. Two assumptions tend to make our EU carbon tax incidence more regressive than if we would account for the following effects: under-reporting in the HBS compared to national accounts and general equilibrium (GE) effects. Using expenditure rather than income as our concept of welfare tends to make our (EU and national) incidences less regressive. Changing the regional and sectoral coverage of the carbon tax, though, affects the regressivity of the carbon tax only weakly. Other channels through which our results might be biased are business cycle effects (income, prices or interest rates effects), heterogeneity in the responses to the tax both across individuals and countries, the capacity of the economy to decarbonize conditional on the state of the technology or alternative socioeconomic or political reasons, such as a pandemic or a deep crisis. We leave it for future research to include these effects.

6. Conclusion

Based on a consistent dataset and a harmonized method, we show that a carbon tax is neutral or even progressive for most of the member states in the EU. For the EU as a whole, however, a carbon tax is regressive which is mainly driven by inter-country differences. These results are robust under a wide range of scenarios. More ambitious climate policy, as is envisioned by the EC in its Green Deal, needs to counter a disproportionately high burden on low-income households. These households are concentrated in a couple of low-income countries. This issue should therefore not be handled at the member-state level alone but by transfers between countries. The fact that inter-country differences are the drivers behind the regressivity of a European carbon tax may be an indication of the existence of an analogous problem on the world scale, where income differences are large and payments from rich countries to low-income countries are likely to be a crucial element in any global climate deal.

With the comparison of the initial burden caused by both direct and indirect uses of carbon, this paper contributes to a number of debates, notably those that focus on responsibility for climate change and indirect (imported) emissions and the territorial principle. We show the importance of studying the various components of direct and indirect carbon tax incidence in different sectors, social strata, countries, and through border carbon adjustments in designing compensatory measures for any inequitable effects that may remain. We find that a sectoral expansion of the EU ETS and a carbon border adjustment would have a progressive effect at the European scale. Hence, these two modifications of the European climate policy can shift the disproportional burden on low-income households towards the richer households at the European scale.

[11] Austria and the Netherlands are not part of the HBS 2010.

[12] According to the statistical bureau of the Czech Republic, the Czech data in the HBS is not suited to deduce aggregate numbers. As we need aggregate expenditure levels to compute national carbon intensities per sector, we exclude the Czech Republic from our central scenario.

[13] Swedish data does not report expenditures at the 5-digit-level for some expenditure categories. While we are able to solve this issue for Germany via using the Consumer Basket, the information from the Swedish Consumer Basket does not solve this issue, e.g. in the category "electricity, gas and other fuels". In this category, valid information is of particular importance for both the direct footprint and the footprint caused by electricity consumption. We thus decide to exclude Sweden in the central scenario.

[14] Again, we correct for Purchasing Power Parity and household size (according to the modified OECD scale) differences.

A particular focus of our study is that of hardship cases occurring when individuals in low-income distribution quantiles face high carbon-tax incidence. By identifying the geographical and social characteristics of these individuals, it may be possible to design other policies to ease their transition to lower carbon use. According to our findings, we propose two European redistribution mechanisms targeted at these especially affected households avoiding high burdens from the tax. We suggest that a variant of the Targeted transfers and high-intensity consumer share that we propose could be incorporated into a European redistribution scheme, for example, the one defined in the allocation rule of the Just Transition Mechanism.

The EC should take due account of national characteristics and employ suitable, transparent communication strategies. Acknowledging that carbon pricing imposes significant short-term costs on households and communicating the fact that policy measures are being taken to avoid this initial impact will make it more likely for future EU climate policy to be successful and accepted by European citizens.

Appendix A. Additional figures and tables

Table A.1
Matching table between GTAP 9 sectors and COICOP-HBS consumption category.

GTAP 9 Sector	COICOP-HBS consumption category
1	01111
4	01161-7,01171-4,01177-8
8	01192, 06121, 09331
10	01147
11	01146
15	04541
19	01121, 01123-5, 01127, 01155
20	01122, 01126
21	01152-4
22	01141-5.01151
24	01181
25	01112-6,01131-4,01168-9,01175-6,01182-6,01191,01193-4,01213,01223-4,02121
26	01211-2,01221-2,02111, 02122, 02131, 02211-3
27	03111, 03131, 05121, 05211
28	03121-3
29	03211-3
31	09511, 09521, 09531, 09541
32	04531, 07221
33	05611, 06111
38	07111, 07121
39	07131, 07141, 07211
40	08211, 09111-2
41	05311-7, 05321, 05411-3, 05511, 05521, 06131, 09121-2, 09131, 09141, 12121, 12311
42	04311, 05111, 05612, 09211, 09221-2, 09311, 09321, 12131, 12321-2
43	04511
44 & 17	04521-2, 04551
45	04411
47	03141, 03221, 05131, 05331, 05414, 07112, 07231, 09151, 09341, 11111-2, 11121, 11211
48	07311, 07321, 07351, 07361, 096
49	07341
50	07331
51	08111, 08311
52	1261, 12621
53	1251, 12521, 12531, 12541, 12551
54	04111, 04121
55	04321, 04441, 05621-2, 07241, 09231, 09411,09421-4, 09431, 12111, 12211, 127
56	04421, 04431, 06211, 06221, 06231–3, 06311, 09351, 10111, 10211, 10311, 10411, 10511, 12411-2
57	04211, 04221-2

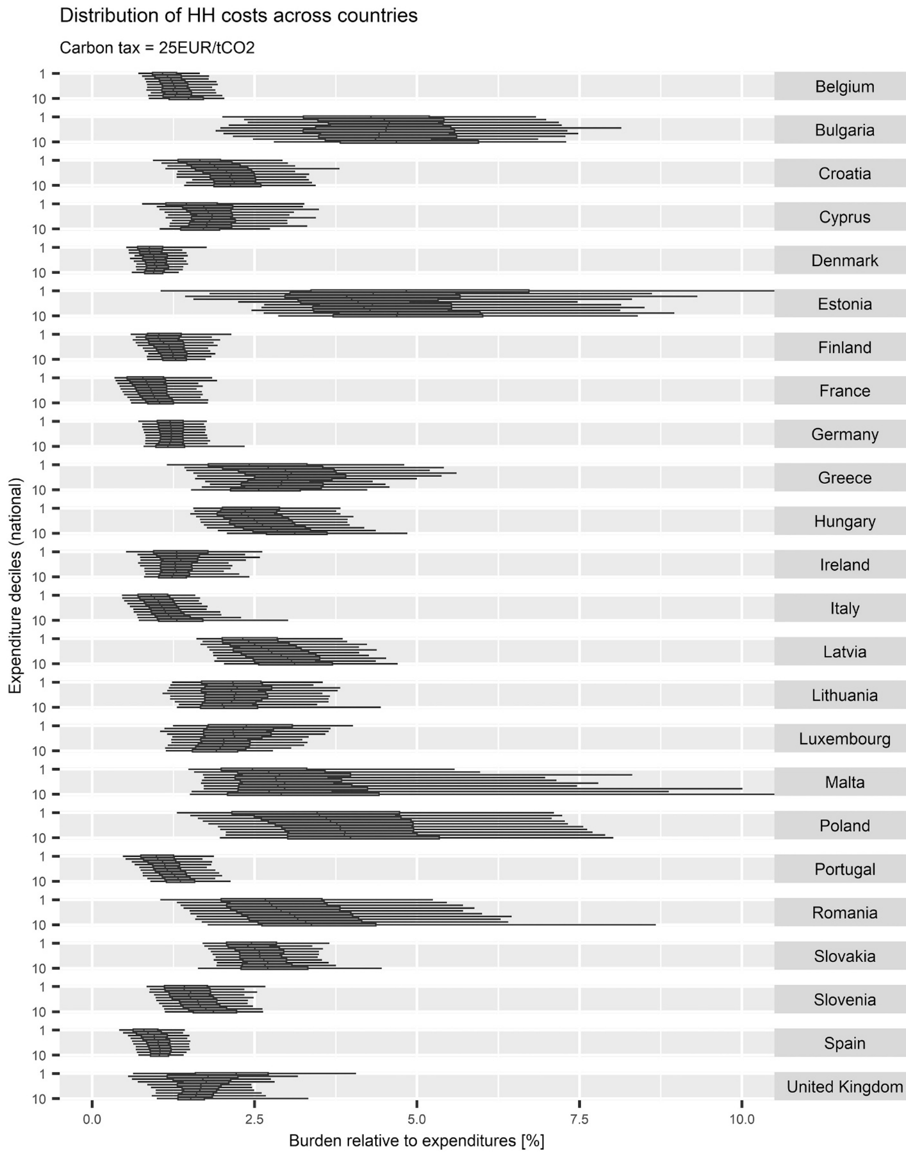

Fig. A.1. National carbon tax burden prior to revenue recycling in 23 EU countries and the UK based on national expenditure deciles. The black line marks the median value per decile. The grey box represents the range of the 25th to the 75th percentile (interquartile range). The whisker below (above) the grey box ends at the 5th (95th) percentile.

Table A.2
Population share per country per European expenditure decile.

Country	Decile									
	1	2	3	4	5	6	7	8	9	10
Belgium	0.41	1.13	1.54	2.34	2.92	3.41	4.08	4.56	4.28	3.91
Bulgaria	10.8	3.65	2	1.08	0.3	0.14	0.14	0.03	0.02	0.01
Croatia	1.6	1.84	1.63	1.24	1.03	0.55	0.42	0.24	0.18	0.06
Cyprus	0.03	0.06	0.09	0.13	0.14	0.16	0.19	0.2	0.28	0.41
Denmark	0.09	0.36	0.88	1.33	1.85	2.29	2.25	2.51	2.48	1.84
Estonia	1.82	0.67	0.42	0.25	0.19	0.13	0.08	0.06	0.06	0.02
Finland	0.48	0.97	1.52	1.6	1.76	1.85	1.63	2.09	1.87	2.05
France	7.06	10.86	14.02	16.61	18.32	20.65	21.65	20.99	22.41	21.38
Germany	1.54	11.84	19.64	23.77	27.33	28.64	29.82	31.02	30.09	31.97
Greece	1.11	2.61	3.02	2.71	2.86	2.74	2.59	2.29	2.54	2.72
Hungary	5.75	6.1	4.41	3.2	1.97	1.24	0.8	0.59	0.27	0.11
Ireland	0.28	0.5	0.69	0.89	0.92	0.94	1.17	1.18	1.28	1.06
Italy	6.92	12.74	13.57	15.52	16.43	16.26	16.66	17.41	17.57	18.77
Latvia	2.47	1.03	0.62	0.38	0.22	0.17	0.08	0.08	0.06	0.05
Lithuania	2.34	1.52	1.2	0.89	0.6	0.51	0.3	0.21	0.14	0.09
Luxembourg	0.01	0.02	0.04	0.06	0.09	0.1	0.11	0.17	0.23	0.4

(*continued on next page*)

Table A.2 (*continued*)

Country	Decile									
	1	2	3	4	5	6	7	8	9	10
Malta	0.11	0.1	0.11	0.11	0.09	0.08	0.07	0.07	0.06	0.07
Poland	22.09	19.58	13.13	9.04	5.96	3.95	2.74	2.01	1.59	1.21
Portugal	3.58	3.51	3.14	2.86	2.26	2.19	1.85	1.77	1.61	1.88
Romania	25	9.34	5.02	2.78	1.41	0.76	0.42	0.22	0.12	0.06
Slovakia	2.23	3.41	2.48	1.5	0.9	0.44	0.33	0.17	0.13	0.07
Slovenia	0.17	0.39	0.57	0.69	0.68	0.62	0.61	0.43	0.37	0.33
Spain	4.13	7.76	10.28	11.02	11.78	12.17	11.99	11.72	12.36	11.51

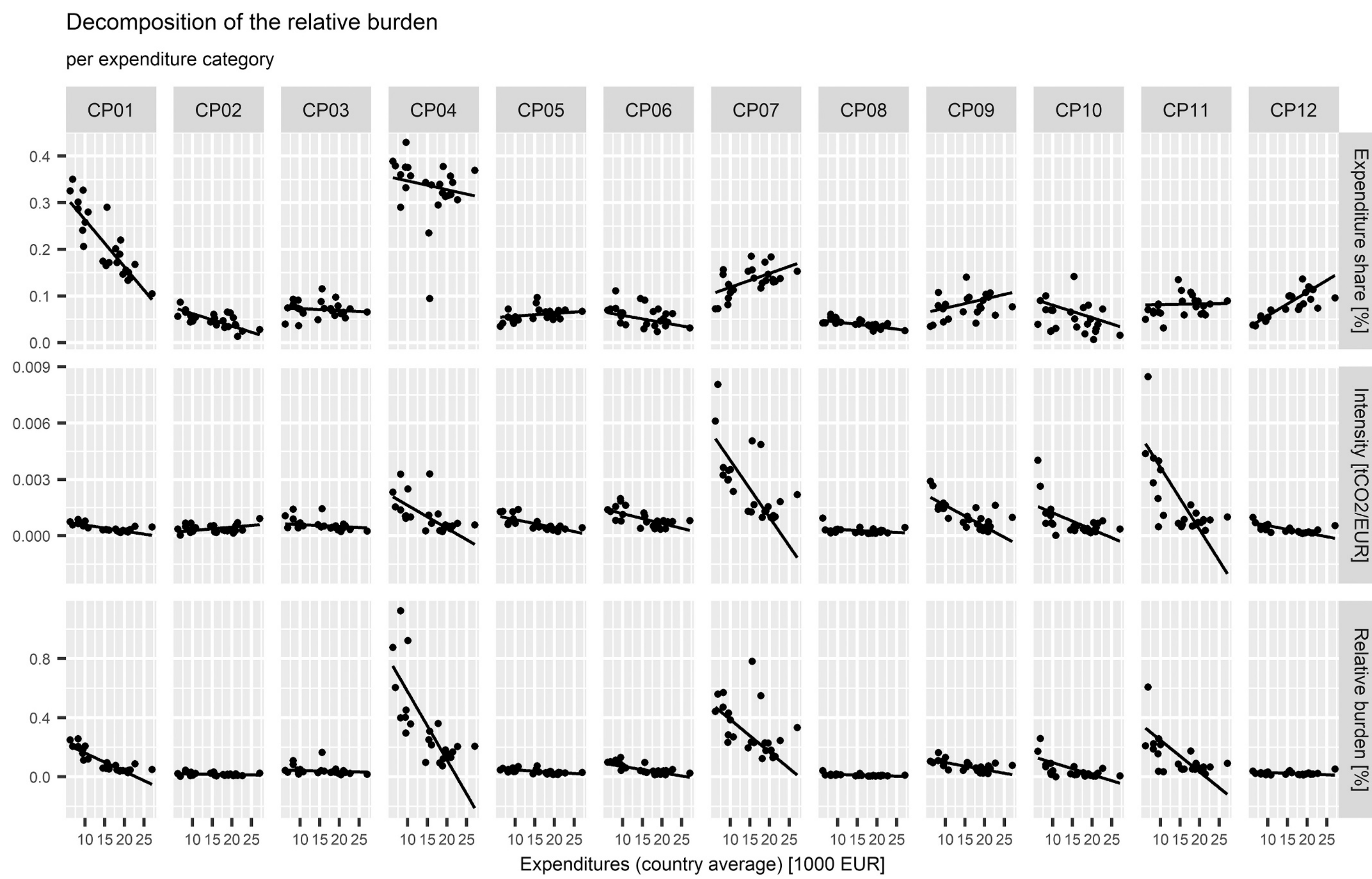

Fig. A.2. Each country's contribution to European carbon tax impact by economic sector. National indicators are plotted against each country's average expenditure. The first row shows the average household expenditure share of the respective sector, the second the carbon intensity in each sector, the third the average carbon tax burden originating from each sector. The tax burden depicted in the third row is the product of the values of the two other rows. The line in each plot represents the linear fit to guide the eye. The twelve sectors are CP01 - "Food and non-alcoholic beverages", CP02 – "Alcoholic beverages, tobacco and narcotics", CP03 – "Clothing and footwear", CP04 – "Housing, water, electricity, gas and other fuels", CP05 - "Furnishings, household equipment and routine maintenance of the house", CP06 – "Health", CP07 – "Transport", CP08 – "Communication", CP09 – "Recreation and culture", CP10 – "Education", CP11 – "Restaurants and Hotels", CP12 – "Miscellaneous goods and services". The 2-digit aggregation level of expenditures is the highest aggregation level below total household expenditures. We calculate carbon intensity per 2-digit consumption category as follows. In the first step, we sum all emissions per country of the 5-digit categories that fall in the respective 2-digit categories. We repeat this procedure for expenditures. In the last step, we divide total emissions per 2-digit category by total expenditure per 2 digit category in this country. In order to derive the expenditure share per 2-digit category, we divide total expenditures per 2-digit category per country by total expenditures (the sum of all 12 2-digit category total expenditures).

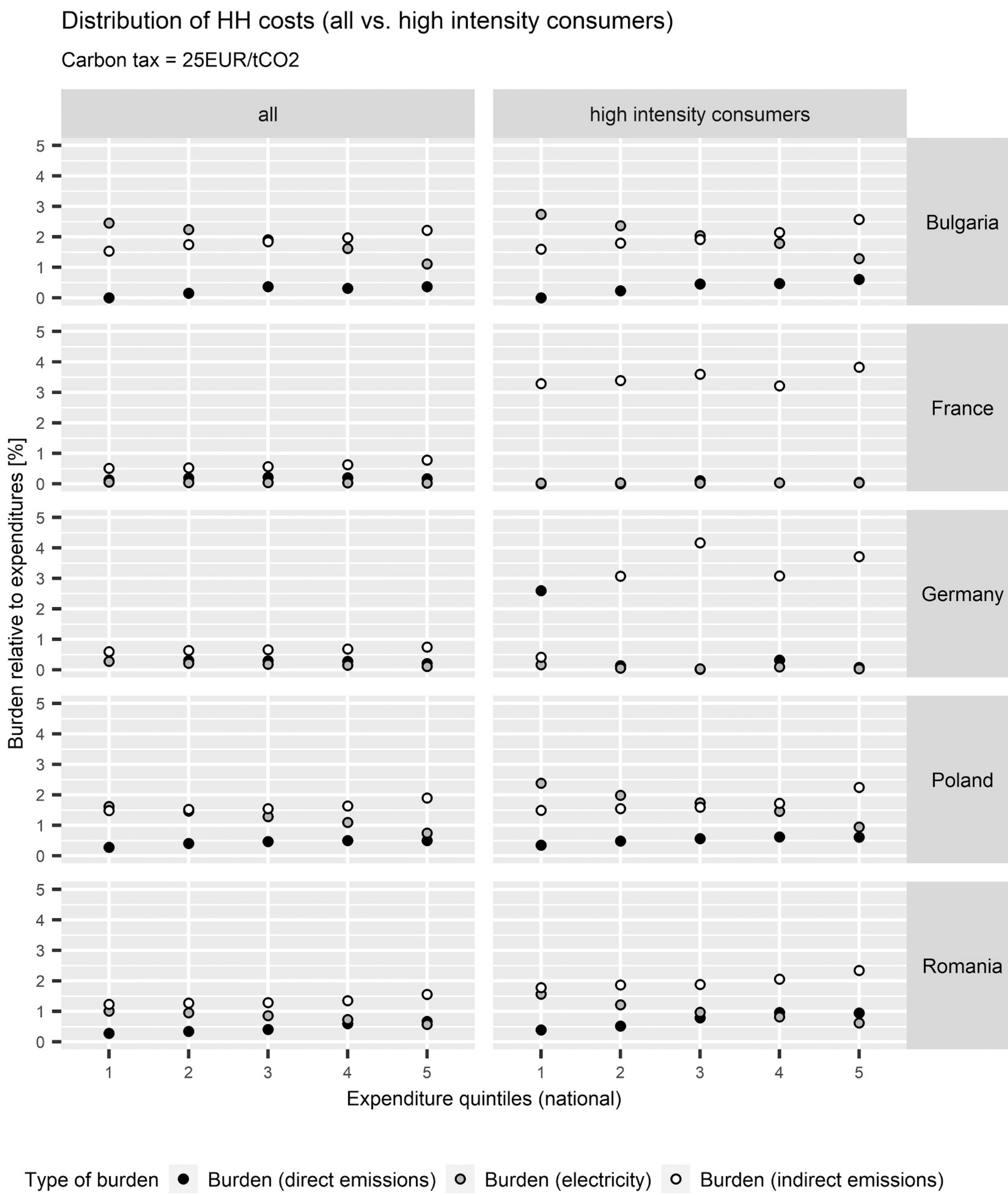

Fig. A.3. Tax burden for high-intensity consumers in selected countries by type of burden. T'he figure compares the median tax burden of high-intensity cases to the median of the overall population sorted by expenditure quintiles in Bulgaria, France, Germany, Poland, and Romania. Quintiles were chosen because of the low number of high-intensity cases in France and Germany. In Bulgaria, Poland, and Romania we see no difference in consumption patterns leading to the high burden. These households are simply poorer and therefore bear a higher burden. In Germany, we observe that cases of high-intensity are driven by direct emissions in the lowest quintile and by indirect emissions in the other quintiles. However, the number of observations is fairly low, so we refrain from generalizations. The number of observations is also low in France, so we do not interpret the pattern in Figure. A closer look at high-intensity consumers based on national distributions may reveal a more reliable pattern.

Table A.3
Demand side elasticities per GTAP 9 Sector based on Labandeira et al. (2017).

GTAP 9 sector	Elasticity estimate [Max, Central, Min]
15	−0.4, −0.35, −0.3
32	−0.29, −0.2215, −0.153
43	−0.18, −0.153, −0.123
44 & 17	−0.18, −0.153, −0.123
48	−0.551, −0.321, −0.091
49	−0.28, −0.16, −0.04
50	−1.4, −1.165, −0.93

Table A.4
Share of aggregated HBS expenditure to EUROSTAT national accounts and GTAP data.

	EUROSTAT	GTAP		EUROSTAT	GTAP
Belgium	0,88	0,87	Latvia	0,61	0,51
Bulgaria	0,58	0,61	Lithuania	0,67	0,59
Denmark	0,92	1,13	Luxembourg	0,90	0,56
Germany	0,82	0,87	Hungary	0,67	0,63
Estonia	0,63	0,59	Malta	0,75	0,48
Ireland	0,73	1,03	Poland	0,56	0,60
Greece	0,76	0,84	Portugal	0,72	0,85
Spain	0,83	0,91	Romania	0,52	0,47
France	0,81	0,88	Slovenia	0,87	0,90
Croatia	0,70	0,73	Slovakia	0,53	0,57
Italy	0,74	0,83	Finland	0,90	0,96
Cyprus	0,83	0,93			

Appendix B. Regression analysis

We specify a linear regression with the dependent variable being the relative tax burden on consumption based CO_2 emissions on equivalent total expenditure corrected for PPP and household size (OECD-modified scale). We use different sets of explanatory variables. The results are summarized in Table A.5. The first regression only includes expenditure and we get a significantly different from zero negative sign. This negative sign can be interpreted as the partial first derivative of the relative tax burden with respect to expenditure. It provides information about the distributional impact across expenditure levels of the tax, with a negative (positive) sign indicating regressivity (progressivity). A non-significant parameter estimate indicates no significant evidence for either regressivity or progressivity, thus a hint for proportionality. In a second specification, we include a quadratic term in expenditure to capture non-linear profiles across the expenditure distribution. The coefficient of the linear term remains negative and significant and the parameter estimate of the square term is positive and significantly different from zero. The threshold where the derivative changes its sign correspond to very high expenditure values indicating that the change in regressivity to progressivity happens at the very top of the distribution (only for a small proportion of households). Fig. 1 exactly shows this relationship: regressivity at the lower half of the expenditure distribution followed by a tendency for progressivity at the richest expenditure deciles. Since estimates are obtained by ordinary least squares, the model just exploits the total variation of the relative tax burden.

In our subsequent specifications, we introduce country dummies. Thus, the parameter estimates of the coefficients correspond to the overall within-country effect, thus only exploiting this source of variation. We get the reverse sign for the coefficients of expenditures, indicating the direction of within-country variations, already reported in Fig. 2. The country coefficients are to be interpreted as the difference of the relative tax burden of a household from Belgium (base category) and a household from a given country, ceteris paribus. A small, insignificant coefficient indicates no significant differences between this country and Belgium. A positive (negative) significant coefficient corresponds to a higher (lower) relative tax burden when originating from a given country compared to originating from Belgium, ceteris paribus. Comparing the estimates in columns (1) and (2) with the estimates including country dummies -columns (3) and (4)-, we can infer that the pattern of regressive results could be mainly explained by between-country differences (a result shown in the corresponding panels of Fig. 2).

We estimate additional specifications including density of population indicators. We obtain significantly higher tax burdens for households living in intermediate and sparsely populated areas compared to densely populated areas (which is the reference group here). As the effect increases from intermediate to sparse population density, one can conclude that the lower the density level, the higher the relative tax burden (ceteris paribus). However, the effect of the population density level is small compared to the size of the most pronounced country effects.

It is possible that misspecification arising from exclusion of relevant factors explaining the relative tax burden drives these results. However, the inclusion of country and density dummies confirm our results from the decomposition method and the visual inspection of the data in Section 3: the carbon tax is regressive at the European scale, and this is driven mostly by between-country differences.

Table A.5
Regression analysis to distinguish between- vs within-country drivers to European regressivity.

	Dependent variable: relative burden			
	1	2	3	4
Expenditures	−0.00004*** (0.00000)	−0.0001*** (0.00000)	0.00001*** (0.00000)	0.00001*** (0.00000)
Expenditures squared		0.000*** (0.000)	−0.000*** (0.000)	−0.000*** (0.000)
Bulgaria			3.493*** (0.029)	3.420*** (0.027)
Croatia			0.944*** (0.028)	0.849*** (0.026)
Cyprus			0.611*** (0.030)	0.579*** (0.028)
Denmark			−0.306*** (0.031)	−0.380*** (0.029)
Estonia			4.054*** (0.027)	3.943*** (0.026)
Finland			−0.040 (0.027)	−0.051** (0.025)
France			−0.282*** (0.019)	−0.339*** (0.018)
Germany			−0.052*** (0.017)	−0.068*** (0.015)
Greece			1.688*** (0.027)	1.626*** (0.025)
Hungary			1.543*** (0.021)	1.462*** (0.019)
Ireland			0.086*** (0.023)	0.030 (0.022)
Italy			−0.101*** (0.018)	−0.142*** (0.017)
Latvia			1.664*** (0.027)	1.589*** (0.025)
Lithuania			1.140*** (0.023)	1.047*** (0.022)

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Table A.5 (*continued*)

	Dependent variable: relative burden			
	1	2	3	4
Luxembourg			0.863*** (0.027)	0.829*** (0.025)
Malta			2.268*** (0.027)	2.312*** (0.025)
Poland			2.912*** (0.017)	2.840*** (0.016)
Portugal			−0.048** (0.021)	−0.126*** (0.019)
Romania			2.033*** (0.018)	
Slovakia			1.421*** (0.023)	1.317*** (0.022)
Slovenia			0.397*** (0.026)	0.297*** (0.024)
Spain			−0.267*** (0.018)	−0.312*** (0.017)
Density: Intermediate				0.157*** (0.006)
Density: Sparsely				0.231*** (0.006)
Constant	2.777*** (0.006)	3.145*** (0.007)	1.113*** (0.017)	1.063*** (0.017)
Observations	265,005	265,005	265,005	233,239
R^2	0.064	0.090	0.459	0.503
Adjusted R^2	0.064	0.090	0.459	0.503
Residual Std. Error	1.737 (df = 265,003)	1.712 (df = 265,002)	1.320 (df = 264,980)	1.225 (df = 233,213)
F Statistic	18,159.040*** (df = 1; 265,003)	13,119.630*** (df = 2; 265,002)	9384.639*** (df = 24; 264,980)	9457.472*** (df = 25; 233,213)

*p < 0.1; **p < 0.05; ***p < 0.01.

Appendix C. Additional scenario description

C.1. Demand side responses and GE effects

As discussed in Dorband et al. (2019), there are typically three main adjustment processes after the introduction of a carbon tax: demand-side changes, supply-side changes, and changes in wages and interest rates. We here address only the first adjustment process, demand side changes, for two reasons. First, demand side changes occur relatively fast after the introduction of a tax (see Baker and Blundell, 1991, for an example using household microdata). Second, including both supply-side changes and changes in wages and interest rates is much more data intensive and contingent upon model assumption (Dorband et al., 2019). As we aim at measuring the initial incidence of a carbon tax, we thus test the robustness of the initial incidence compared to the short-term incidence of a carbon tax via including demand-side responses. In this context, Álvarez (2019) shows, using discrete choice models, differences in the probabilities of obtaining diverging results in microsimulation models with or without demand side responses and GE models. His results reinforce our conclusions, conditional to the set-up we employ. In order to do so, we adopt the methodology applied by Ward et al. (2019) and first detect those sectors that are relatively highly affected by carbon pricing (via their respective carbon intensity). We then apply available elasticity estimates from Labandeira et al. (2017)[15] and let the demand in these sectors adjust as follows: $y_{r,\,s}^{*r'} = y_{r,\,s}^{r'} \bullet (1 + \Delta b_s^r)^{\delta}$, where $y_{r,\,s}^{*r'}$ is the updated demand after the demand-side response and Δb_s^r the price increase of the average final consumption item s in region r. Thus, the modelled emissions would decrease by $y_{r,\,s}^{*r'}/y_{r,\,s}^{r'}$.

As our sample of regions is highly diverse and heterogeneous, we apply two scenarios with heterogeneous elasticities. We cluster the sample of our countries into three regions: Northern European, Eastern European and Southern European countries, assuming that actors in regions X, Y and Z have different abilities to adjust their expenditures. In the first scenario, we assign relatively good adjustment ability to Northern European countries, average ability to Southern European countries and the relatively lowest ability to Eastern European countries. In the second scenario, it is the other way around. Now, Eastern European countries adjust relatively easily and Northern European countries less easy. We again apply average ability to Southern European countries. This scenario mimics the situation that households in countries with a high average carbon tax incidence are better capable of adjusting their consumption. We test these two scenarios because it has been shown that the level of development of a country is a relevant factor for explaining differences in elasticities (see Fouquet, 2014).

Abstracting from behavioral responses in our central scenario can be seen as a rather high threshold for our measure of incidence. To also calculate the lowest possible effect on households after demand responses, we construct a hypothetical scenario. In this scenario, we apply the highest elasticity estimate from Table A4 (−1.4) to all sectors affected and to all countries equally. This scenario also mimics the situation where the consumer response to carbon-tax-induced price changes might be more pronounced than for conventional price changes. Andersson (2019) finds three-times higher elasticity estimates based on Swedish data. Hereby, we approach a lower threshold for the additional burden of the tax, precisely because we command households to react in the most extreme way that has been observed in the past for any good and consumer group. Note that this scenario does not include possible heterogeneous price elasticities across income levels. Banks et al. (1997) show that price elasticities are not constant across the income distribution in a quadratic almost ideal demand system.

Whether price elasticities are very different across the income distribution is still an empirical unsolved question, although recent evidence seems to reinforce existing results that there is no evidence for significant differences of the price elasticity across the income distribution (see e.g. Ortega Díaz and Medlock, 2021). Our guess, based on evidence using quadratic demand models (see Labandeira et al., 2006), is that even when demands for some goods present non-linear profiles, it is not going to affect very much the dispersion of the own-price elasticities and, as a consequence, their effects on post-tax figures. In this sense, we are confident that our results constitute a measure close to a lower threshold in terms of the heterogeneous tax burden across income levels. This narrows down the interval of our results and reduces the uncertainty about the demand-side effects on regressivity.

[15] They report a summary of price elasticities found in the literature both for energy as a whole and for several energy commodities. Since ours can be interpreted as short-run results, we take the average short-run elasticities provided in their meta-analysis.

C.2. Under-reporting

Under-reporting leads to two issues. First, we underestimate total expenditure levels of households. The ranking of households in the EU expenditure distribution could therefore be incorrect. We refrain from some form of correcting household expenditure because the HBS is the best data we have on household consumption.[16] Second, we overestimate sectoral carbon intensities because we derive the intensities with aggregate HBS expenditures.

Based on the national final consumption expenditure data provided by EUROSTAT[17], we calculate the fraction of under-reporting at the 3-digit COICOP level. The assumption behind this approach is that EUROSTAT aggregate data is more accurate than aggregating household expenditure data from the HBS. We then use the fraction of under-reporting to inflate aggregate HBS expenditures. In order to be able to maintain the same matching as described in Section 3.3, we apply the fraction of under-reporting from the 3-digit-level to the subordinate expenditure categories at the 5-digit level. In the final step, we use the corrected aggregate expenditures at the 5-digit level to calculate corrected carbon intensities. This correction can have heterogeneous effects on households between and within countries. As for example average under-reporting is higher in e.g. Bulgaria than in Denmark (see Table A3), the corrected tax burden in Bulgaria decreases more strongly than in Denmark. Within countries, differences between expenditure sectors matter, too. Reducing for example the carbon intensity of the electricity sector more strongly than other carbon intensities leads to relatively higher changes for those households spending relatively more on electricity (usually the poor). Thus, we correct partly for both the heterogeneous effect of underreporting across countries and across income groups.

Our second approach to tackle under-reporting is to derive sectoral carbon intensities with GTAP 9 sectoral household expenditure estimates. GTAP explicitly accounts for households' imports at market prices and households' domestic purchases at market prices for their sectors (Aguiar et al., 2016).

In both approaches, we stick to the method described in 2.1 for the derivation of the CO_2 emission vector F, but now use the two different total sectoral expenditure vectors for the calculation of the CO_2 intensity vector f.[18]

C.3. EU 27

Austria, the Netherlands, the Czech Republic and Sweden are excluded from our central scenario. Based on EUROSTAT's dataset on expenditures by income quintile we include these four countries in a sensitivity scenario. The data contains info on the average expenditure shares of the income quintiles on consumption goods at the 3-digit-level and on average total expenditure levels. We combine the 3-digit-level data with the dataset on average expenditure shares (total population – not by income quintile) which is provided at the 4-digit-level to arrive at household expenditure by income quintile at the 4-digit level.[19] Drawbacks of this dataset are threefold. First, households are ranked according to their income instead of expenditure levels. Second, we can only build on average figures per quintile. Third, the highest level of resolution is the 4-digit-level. As there is no data available on how the 4-digit-level expenditures can be split into the 5-digit-level, we assume that the expenditures are equally spent on the respective subcategories.

C.4. EU 23 + UK

To account for the possibility that the UK remains part of the European climate policy, we model a scenario with the original 23 countries plus UK. The calculation is straightforward and analogous to our central scenario, as the UK is part of the HBS 2010 and the GTAP 9 data.

C.5. Carbon tax on domestic emissions with and without CBA

The European Trading Scheme (EU ETS) regulates local CO_2 emissions within specific sectors, with around 11,000 large sources (industries, power stations) and airlines covering roughly 45% of total EU greenhouse gas emissions (Bayer and Aklin, 2020). In phase I, it covered around 50% of total CO_2. The European Commission proposes to increase the sectoral coverage of the EU ETS and to consider border carbon adjustments in case of a lack of international ambition. We include two sensitivity tests addressing the possibility that these two extensions will not happen. For the first test, taxing only on domestic EU emissions, we modify the vector f introduced in Section 3.1 as follows. All direct CO_2 emissions outside the EU (so all emissions related to non-EU industrial sectors) are set to zero, resulting in a refined vector f^{*EU}. This vector is then used for the analysis. This scenario covers 73% of total embodied emissions.

In the second scenario, we analyze the initial burden resulting from the EU ETS only. The tax is imposed only on emissions produced and consumed within the EU and within those sectors that are covered in Phase III. GTAP sectors covered are sectors 16, 31, 32, 33, 34, 35, 36, 43 and 50. Since we have no information about the distribution of emissions within the GTAP sectors, we assume that a GTAP sector is fully taxed if it is partly covered by the EU ETS. In Sectors 16, 31, 32, 34 and 43 we thus likely tax more emissions than covered within Phase III, resulting in an over-estimation of the tax burden of the EU-ETS. This scenario is modelled analogously to the previous one. Now, f is calculated as follows. All direct CO_2 not related EU-ETS industrial sectors are set to zero. We get a refined vector $f^{*EU-ETS}$, which is used for the analysis. Overall, 54% of total embodied emissions are now regulated.

[16] Inspecting Table A.4 shows that under-reporting is higher in lower-income countries like Bulgaria, Poland or Romania. Since these countries drive our regressivity result as they populate the lower deciles of the distribution, we conjecture that not correcting for under-reporting in total expenditure likely makes our central estimate too regressive.

[17] Data identifier nama_10_co3_p3

[18] Please note that this changes total emission levels assigned to households, too.

[19] We use the dataset by income quintile to get the expenditure level by 3-digit sectoral resolution for each quintile. From the dataset on the average expenditure shares at the national level, we can calculate how much is spent from these respective expenditures on the subordinate categories at the 4-digit level. By making the assumption that the share spent from the 3-digit-category on the subordinate categories is equal across income quintiles, we arrive at expenditure patterns at the 4-digit level by income quintile.

Appendix D. Suits index

We calculate the Suits index according to Suits (1997). The Suits index is given by

$$S = 1 - \left(\frac{1}{K}\right)\int_0^{100} T_x(y)d_y,$$

where T_x is the relative accumulated tax burden of the respective household, y the relative accumulated expenditure (from 0 to 100), and $K = 5000$. We approximate the integral $\int_0^{100} T_x(y)d_y$ by calculating the area under the curve with the trapezoidal rule that connects all points by a straight line:

$$S \approx 1 - \left(\frac{1}{K}\right)\sum_{i=1}^{N} 0.5(T(y_i) + T(y_{i-1}))(y_i - y_{i-1}),$$

with N being the number of households. This allows us to use household-level data instead of relying on decile averages as described in Suits (1997) in the case of discrete data. The Suits index is positive (negative) for a progressive (regressive) tax, ranging from $-1 \leq S \leq 1$. To rank the households according to their expenditure level and for the calculation of the Suits index, we use the PPP and OECD (modified) adjusted figures and take into account the provided sample weight of each household.

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Distributional Impacts of Carbon Taxation in Mexico

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Distributional Impacts of Carbon Taxation in Mexico

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Abstract

The main aim of this paper is to analyze the different impacts of carbon taxation in Mexican households at different income levels. First, we estimate a household demand system for non-durable goods with special emphasis on energy-related goods. Then, we use the results to simulate the introduction of a carbon tax. We look at the potential to raise revenue with the aim of implementing different redistributive policies in order to address issues of inequality and poverty. Moreover, we evaluate the effects of carbon taxes on demand and emissions reduction.

Keywords: emissions; carbon taxation; distribution; poverty; Mexico

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1. Introduction

Among the commitments of the Paris Agreement (UN, 2015), the signatory countries agreed to reduce their greenhouse gas emissions, translating this commitment into Nationally Determined Contributions (NDCs). Mexico commits unconditionally to reduce its greenhouse gas (GHG) emissions by 22 percent in 2030 compared to the baseline constructed in a baseline scenario estimated for 2013 (991MtCO_2e). In addition, conditional commitments would increase emissions mitigation to 36 percent in 2030 compared to the baseline scenario (Government of Mexico, 2020)[1]. Within Mexican GHG emissions, energy-related emissions stand out, accounting for 63.5 percent of gross GHG emissions and 87.5 percent of net emissions (including removals) in 2019 (SEMARNAT, 2022). It is therefore crucial, to achieve significant reductions in the coming years, to design and implement public policies particularly for the energy sector.

Mexico initiated an energy reform in December 2013 (see Álvarez and Valencia, 2015, SENER, 2015, Vargas, 2015), with the aim of substantially transforming the energy sector. This reform was far reaching by Mexican standards and entailed steps that were earlier considered unthinkable in Mexico such as the elimination of PEMEX's monopoly, as well as the modification of the mechanism for determining tax rates on gasoline (which often resulted in the tax actually being a subsidy), replacing it with fixed tax rates (see Muñoz, 2013). A carbon tax on fossil fuels was also introduced (albeit at too low a rate to trigger behavioural change) and the electricity sector was reformed to try to reduce its costs (see Husar and Kitt, 2016).

These steps were a radical departure with historical precedents in Mexico where politics has been heavily marked by a fierce nationalism that has its origins in the nationalisation of foreign oil companies by President Lázaro Cardenas in 1938. Since at least the 1970s Mexico turned into a major oil producer and exporter with profound effects on the structure of the Mexican economy which showed many of the signs of Dutch disease, (Guevara et al., 2022). During the last thirty years or more, Mexican development has been marked by a dominance of the petroleum sector, low domestic energy prices and the effects this has on (energy intense) technology choice and industrial structure (Sterner 1985, 1989). However, over time this strategy has led to problems such

[1] Fulfilling these commitments involves the international consolidation of technology transfer mechanisms, an international carbon trading price, carbon adjustment tariffs, technical cooperation, access to low-cost financial resources and technology transfer, all on a scale equivalent to the challenge of global climate change.

as the overvaluation of national currency and consequent problems of competitivity for non-petroleum sectors in the economy. Eventually Mexican exports of oil could not sustain the economy and furthermore the challenge of dealing with climate change and other factors have led to a change in policy.

Starting with the change of government in 2018, several measures were put in place however, with the aim of not increasing real energy prices, which limited the scope of the reforms. In particular, a new mechanism for residential electricity tariffs was established, so that they only adjust based on inflation and do so gradually during the year, as well as the so-called "fiscal stimulus", which is approved weekly and involves a reduction in the tax rate on fuels (see Government of Mexico, 2019). This fiscal stimulus initially involved reductions of between 20-40 percent in the tax rate on gasoline, although currently (week of 23-29 April 2022) the fiscal stimulus is 100 percent (SEGOB, 2022), which means that the tax on fuels is not applied. Furthermore, residential electricity tariffs are heavily subsidised, so that, on average, households pay only 46 percent of the total cost of the service (Hancevic et al., 2019), with electricity subsidies amounting to close to 0.3 percent of GDP (73 billion pesos in 2022, see Government of Mexico, 2022).

The 2013 energy reform also provided for the introduction of an emissions trading system. Mexico initiated a 36-month trial ETS programme in 2020, in which only installations operating in the energy and industry sectors whose annual emissions are at least 100,000 tonnes of direct CO_2 emissions participate (SEMARNAT, 2021). While the scheme is expected to be operational from 2023, there is uncertainty both on the timing of its introduction and on the emissions that will be covered by it. In this context of low taxation on energy products and uncertainty about the future emissions trading system, existing public policies are not incentivising energy savings and efficiency, so additional policies are needed to achieve significant reductions in carbon emissions to meet the Paris Agreement commitments. To this end, a carbon tax on energy products can be used at a sufficiently high level to achieve behavioural changes. This policy would also be complementary to the ETS, taxing sectors not covered by the ETS, as well as sectors included in the ETS until it becomes operational.

Therefore, our first objective in this paper is to simulate the environmental, revenue and distributional effects of a CO_2 emissions tax on the main Mexican energy products. Energy taxes have the capacity to generate a relevant volume of public revenue, sometimes at the cost of significant distributional impacts (see Gago et al., 2021). So, our second aim is to explore the introduction of compensatory mechanisms aimed to reduce poverty and inequality using the additional revenue generated by the new tax. Countries such as Mexico that show significant problems of poverty and inequality are unlikely to suffer significant distributional problems, but the extent of pre-existing poverty is so significant that the introduction of compensatory mechanisms may still be very important. Table 1 shows the poverty rate in 2018, i.e., the percentage of households living with less than 60 percent of median income (the poverty line as defined by Foster et al., 1984 or Heindl, 2015 among others) and using household expenditure as a proxy for income. We find that more than 23 per cent of Mexican households are in poverty, especially prominent in the south of the country (over 37 per cent of households in poverty) and in rural areas (almost 43 per cent). Regarding inequality, the Gini index shows that inequality is also higher in the south and in rural areas.

Table 1. Poverty rate and Gini index. 2018

	Total	North	Center	South	Urban	Rural
Poverty rate	23.84	21.15	19.25	37.22	17.98	43.19
Gini index	0.3711	0.3618	0.3594	0.3881	0.3547	0.3686

Note. The poverty rate is a percentage.
Source: Own elaboration with data from INEGI (2022b).

The academic literature on energy demand in Mexico has mainly focused on studying transport fuel demand (Bernt and Botero, 1985; Gately and Streifel, 1997; Eskeland and Feyzioglu, 1997a, 1997b; Galindo and Salinas, 1997; Haro and Ibarrola, 2000; Bauer et al., 2003; Reyes et al., 2010; Crôtte et al., 2010; Solís and Sheinbaum, 2013; Rodriguez-Oreggia and Yepez-Garcia, 2014; Fullerton et al., 2015; Akimaya and Dahl, 2018). Some papers have analysed electricity demand (Berndt and Samaniego, 1984; Chang and Martinez-Chambo, 2003; Salgado and Bernal, 2007; Hancevic and Lopez-Aguilar, 2019). Finally, we find studies on demand for various energy products (Sterner, 1989; Sheinbaum et al., 1996; Galindo, 2005).

On the other hand, the study of energy demand in the context of a complete demand system to analyse the effects of different policies affecting the energy sector has also received attention. Thus, Moshiri and Martinez (2018) study the effects of increases in the prices of energy products as a result of the 2014 Mexican energy reform; Renner et al. (2018) analyse the effects of the introduction of a carbon tax; Rosas-Flores et al. (2017) and Labeaga et al. (2021) study the impacts of the removal of energy subsidies and the introduction of carbon taxes; Ramírez et al. (2021) assess the impact of the 2014 Mexican energy reform; while Ortega and Medlock (2021) study the elasticity of demand for energy products as a function of household income level.

In addition to the aforementioned objectives, this paper aims to update the previous literature by using more recent data and simulating the impacts of introducing higher carbon prices that allow for a significant reduction in GHG emissions associated with energy consumption. To this end, the article is divided into five sections, including this introduction. Section 2 presents the data used and the methodology employed, while Section 3 reports the estimation results of the econometric model used. Section 4 presents the results of the simulations. The paper ends up with a summary and conclusion.

2. Data, variables, and demand system estimation for Mexico

2.1. Data and variables

We use microdata for the period 2006-2018 from the Encuesta Nacional de Ingresos y Gastos del Hogar (ENIGH) published by the Bureau of Statistics of Mexico (INEGI, Instituto Nacional de Estadística y Geografía). It is a biannual survey that uses face-to-face interviews to collect household budget data using stratified random sampling. The survey collects information on the value of household expenditures on different goods and services, providing detailed information on household and housing characteristics (see INEGI, 2022b). The initial sample size is 251,437 observations for all the pooled biannual cross-sections. The characteristics of the data as well as our own objectives make us select the sample as follows. We drop households where several families live, households with no expenditure on food, no expenditure on non-durable goods and households with no income, as well as first top and bottom percentiles of the distributions of total non-durable expenditure and income. This process reduces the sample by 21,142 observations. As we explain latter on, we do further sample selection in specific exercises.

We use the following categories of expenditure[2]: food at home, low octane gasoline (magna), high octane gasoline (premium), liquefied petroleum gases (LPG), electricity, and other non-durable goods[3]. Since our aim is to estimate a flexible Almost Ideal Demand System (either linear or quadratic), we calculate the expenditure shares for each commodity by dividing the expenditure on it by the total expenditure on non-durable goods in the household. As we will see later, in the specification of the demand model we include a wide set of sociodemographic variables whose definitions and descriptive statistic are in Table A1 in Annex A[4]. Thus, 31.7 percent of households live in the north of the country, while 44 percent live in the center and the remaining 24.3 percent in the south. Furthermore, 67.8 percent of households live in urban areas, 63.3 percent own a house without a mortgage, 12.7 percent rent the house where they live, 27 percent own a car, and 48 percent own a vehicle (car, van, pickup and/or motorbike). The household head is, on average 48.8 years old, 25.9 percent of household heads are women, and 10.2 percent report higher education level, while 26.6 percent report having only primary education.

We need price data with as much variation as possible to identify own and cross-price effects. We do have in the ENIGH survey information about the week where the interview took place. From this information, we create the variable month. The INEGI (2022c) considers the price indexes of different goods as well as the Retail Price Index (Índice Nacional de Precios al Consumo, INPC from now on) at monthly level in the cities[5]. INEGI provides price data for 46 cities for the whole

[2] All monetary variables, prices included, has been deflated using the regional Retail Price Index (RPI) to get variables in real terms.
[3] Other non-durable goods include non-alcoholic drinks, alcoholic drinks, tobacco, housing goods for cleaning and caring, goods for personal care, newspapers, stationery not for education, oils, lubricants and additives, candles and candlesticks, other fuels (carboard, paper for burning, etc.), medicines and healing materials, materials for dwelling repairing, photographic material, expenses on gifts to people outside de household (food, drinks and tobacco), diesel and gas for housing, petrol, diesel for transport, wood, fuel for heating and natural gas.
[4] Important variables for the purposes of this paper are geographical location of the household, both Entidad Federativa and municipality. We use the first five digits of variable "ubica_geo", to get Entidad Federativa (two first digits) and municipality (three following digits). These two different location variables are listed (with assigned numbers) in INEGI (2022a). We check that Entidades Federativas are exactly what is usually named Mexican states.
[5] INEGI also provides information for the INPC for Entidades Federativas, but they do it only from 2018, which we introduce.

sample period[6], which we assign to Entidades Federativas[7].

We consider the monthly INPC for cities and we assign each household the price corresponding to the month when the survey was conducted. We consider the following nominal price indexes and the Retail Price Index (to construct and use real prices): food, electricity, LPG[8], magna gasoline, and premium gasoline. To complete a demand system, we add a category of other non-durable goods for which we do not have any information at city level (it implies that we cannot do the previous assignments to Entidades Federativas and municipalities), so the price of other non-durable goods is calculated as a weighted average of prices for alcoholic beverages and tobacco, detergents and similar products, drugs, personal care goods and services, newspapers, and other goods. The weights correspond to the share each household devote to each good[9]. Figure 1 shows some graphical evidence on the evolution of prices.

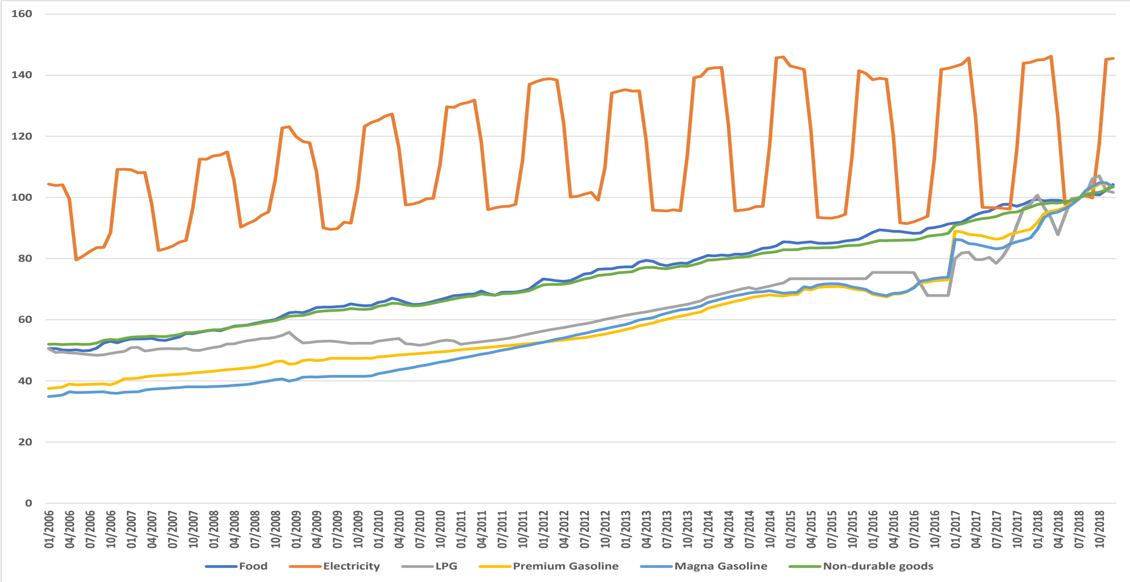
[6] Cities with price data by Entidad Federativa: Aguascalientes (Aguascalientes), Mexicali and Tijuana (Baja California), La Paz (Baja California Sur), Campeche (Campeche), Cd. Acuña, Monclova and Torreón (Coahulia de Zaragoza), Colima (Colima), Tapachula (Chiapas), Cd. Jiménez, Cd. Juárez and Chihuahua (Chihuahua), Ciudad de México (Distrito Federal), Durango (Durango), Cortazar and León (Guanajuato), Acapulco and Iguala (Guerrero), Tulancingo (Hidalgo), Guadalajara and Tepatitlán (Jalisco), Toluca (México), Jacona and Morelia (Michoacán de Ocampo), Cuernavaca (Morelos), Tepic (Nayarit), Monterrey (Nuevo León), Oaxaca and Tehuantepec (Oaxaca), Puebla (Puebla), Querétaro (Querétaro), Chetumal (Quintana Roo), San Luis Potosí (San Luis Potosí), Culiacán (Sinaloa), Hermosillo and Huatabampo (Sonora), Villahermosa (Tabasco), Matamoros and Tampico (Tamaulipas), Tlaxcala (Tlaxcala), Córdoba, San Andrés Tuxtla and Veracruz (Veracruz de Ignacio de la Llave), Mérida (Yucatán), and Fresnillo (Zacatecas).

[7] We assign prices to Entidades Federativas as follows: In those Entidades Federativas with only one city, we consider that the prices of the city correspond to the prices of the Entidad Federativa. If there is a Entidad Federativa with several cities, we calculate a population-weighted average of prices for the whole Entidad Federativa and assign these prices to the municipalities of the Entidad Federativa, except to the cities because they have their own price index.

[8] We do not have separated data for LPG and natural gas up to 2011, so from 2006 to 2010 we use the aggregate of two expenditures.

[9] We have a problem to calculate or impute prices for other energy sources (petrol and diesel for housing, carbon, wood, natural gas and other fuels). We have tried several alternatives as impute averages (and minimum) prices of energy sources, weighted by expenditure shares of consumed goods by the household. We do have however an imputation problem with the final number of observations remaining. Since only 32,588 out of 251,437 observations provide positive expenditure on other non-durable goods, a second alternative is to impute average (or minimum) prices of other sources both by groups of expenditure and location. Real prices are again computed using regional RPI. The price of other non-durable goods is calculated as a weighted average of prices of all other non-durable goods outside this group, being the weights the household expenditure. Another alternative we try is to impute this price with the existing price of one (or several) of the components of the non-durables.

Figure 1. Prices evolution (second half of July 2018 = 100)



Notes:
This graph shows the evolution of prices at the national level, although, as indicated above, we use city-level prices in our analysis. The electricity price profile is due to the existence of electricity subsidies in places that face high temperatures during the summer (minimum average temperature above 25ºC, see CFE, 2022).
Source: INEGI (2022c)

2.2. Demand system

We have proceeded in several steps to estimate the demand system. All systems we estimate allow for quadratic effects (i.e., demand systems of rank three) to allow for flexible income responses. So, we base our theoretical model on the Almost Ideal Demand System (AIDS) of Deaton and Muellbauer (1980) and the Quadratic Almost Ideal Demand System (QUAIDS) of Banks et al. (1997)[10]. The QUAIDS assumes the following cost function:

$$ln\ c(u,p) = ln\ a(p) + \frac{ln\ u\ b(p)}{1-\lambda(p) ln\ u} \qquad [1]$$

where *u* is utility, *p* is a set of prices, *a(p)* is a function that is homogenous of degree one in prices, *b(p)* and *λ(p)* are functions that are homogenous of degree zero in prices. Accordingly, the indirect

[10] Details about these two demand models are provided in Deaton and Muellbauer (1980) and Banks et al. (1997) and we omit the details in this paper. It is possible to compare AIDS and QUAIDS elasticities with alternative more flexible results obtained using Exact Affine Stone Index (EASI) demand system proposed by Lewbel and Pendakur (2009). However, this is out of the scope of this paper.

utility function is:

$$\ln V = \left\{ \left[\frac{\ln m - \ln a(p)}{b(p)} \right]^{-1} + \lambda(p) \right\}^{-1} \qquad [2]$$

where *m* is total expenditure, *ln a(p)* and *b(p)* are the translog and Cobb-Douglas functions of prices defined as:

$$\ln a(p) = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln p_i + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \gamma_{ij} \ln p_i \ln p_j \qquad b(p) = \prod_{i=1}^{n} p_i^{\beta_i} \qquad [3]$$

where p_i and p_j are price indices of goods *i* and *j*, respectively. $\lambda(p)$ is a differentiable, homogenous function of degree zero in prices, and defined as $\lambda(p) = \sum_{i}^{n} \lambda_i \ln p_i$.

The model we estimate is expressed in expenditure shares for each of the goods within total non-durable expenditures. We can derive these equations by applying Shephard's lemma to the cost function [1] or Roy's identity to the indirect utility function [2]. As usual, the demand should satisfy additivity of budget shares, homogeneity of price responses and Slutsky symmetry. We impose additivity by omitting one equation out of the system during the estimation. Homogeneity in single equations is imposed by expressing prices in relative terms to the excluded good. System-homogeneity and Slutsky symmetry concern the whole demand system and cannot be imposed, but we test for them after estimation.

One additional feature of our system is that we have gasoline in our set of goods, for which we observe a non-negligible proportion of zero expenditures. The literature shows (see for instance Labeaga and López, 1997) that they correspond mainly to non-participants, i.e., individuals (households) who do not own a vehicle. So, we assume that households take owning before demand decisions. We propose to estimate a probit model in the first stage and calculate the Inverse Mills Ratio (IMR) that, in turn, is used to correct the budget share equations of all goods at the second stage (see Labeaga and López, 1997 or Labeaga et al., 2021). Given that, to simulate the proposed reforms, we need not only the estimated parameters for owners but for the whole population, we also estimate the equations for non-owners (i.e., a kind of Roy model as described by Cameron and Trivedi, 2005, for instance), but for the whole system of equations.

3. Results

We faced several problems in the separate estimation of two very similar types of gasoline (premium and regular). Demand for these products is related to vehicle ownership in a complex manner, first of all to the type of vehicle (extensive margin) but also to the distance driven (intensive margin), We therefore propose the estimation of unconditional and conditional demand models in the spirit of Browning and Meghir (1991) but modelling the decision on ownership as explained before. Given data problems the large number of zeros, we test our estimations and found that separating two different gasolines, magna and premium, does not produce adequate results. Hence, we estimate the demand for aggregate gasoline.

Tables B1-B3 in Appendix B show the estimation results. We observe that prices, household income and many household and housing characteristics are key factors explaining the expenditure shares on food and energy goods. Among sociodemographic variables, geographic location and vehicle ownership appear as relevant demand determinants.

We find, all other variables constant, that the expenditure shares on electricity, are higher in Northern Mexico than in the South. They are also higher in the center for households without a vehicle, but lower for households with a vehicle.

In the case of food, the expenditure share is lower in the north, and in the center but only for households without a vehicle, compared to the south. In turn, the share of LPG expenditure is higher in the north and in the center, while the share of gasoline expenditure is higher in the north and lower in the center, also compared to the south. On the other hand, the significance of income in quadratic terms in all models for all products shows that income effects are not linear.

With respect to price elasticities (see Table 2), the results show that both food and energy products are inelastic goods, with price elasticities being higher, in absolute value, for households without vehicle. Our guess is that the reason behind these results is that owners are richer than non-owners, so that, they are in a better position to face any price shocks. Those who are poor are more motivated – or obliged to adapt to changing prices and their price elasticities therefore higher, while those with more money can afford to pay less attention to price changes. We compare price elasticities across different papers in the literature and we find that our price elasticity of food is similar to that obtained by Ramírez et al. (2021) and it lies within the range of elasticities estimated by Attanasio et al. (2013) for different types of food in Mexico, while the price elasticity of gasoline is also similar to that obtained by Ramírez et al. (2021). The price elasticity of electricity is similar to that estimated by Rosas-Flores et al. (2017), Ortega and Medlock (2021) or Ramírez et al. (2021), while the price elasticity of LPG is in the range of the elasticities estimated by Rosas-Flores et al. (2017) and Labeaga et al. (2021).

For total expenditure elasticities (Table 2), the estimation results show that gasoline and electricity are luxury goods, while food and LPG are normal goods. This suggests that higher energy taxes would fall mainly on the rich. In the case of gasoline, Renner et al. (2018), Ortega and Medlock (2021), Labeaga et al. (2021) or Ramírez et al. (2021) also identify it as a luxury good, while for food the results are similar to those obtained by Renner et al. (2018). In the case of LPG, Rosas-Flores et al. (2017) also identify it as a normal good, while for electricity the results are like those obtained by Labeaga et al. (2021) for households without a vehicle.

If we compare the results of the non-conditional model with the results for households with and without a car, we see that, as indicated above, the price elasticities are higher for households without a vehicle than for households with a vehicle, with the price elasticities of the non-conditional model lying between these values. With respect to income elasticities, they are higher for households without a vehicle than for households with a vehicle (except in the case of food, which are similar). This result may be due to households without a vehicle are generally poorer than households with a vehicle, so their energy consumption is more likely to be below their desired consumption and also because richer households have more substitution possibilities. In this context, given an increase in income, their energy consumption can be expected to increase more (due to the acquisition of energy-consuming durables that were previously unavailable to them) than that of households with a car, which are more likely to already have such durables and are consuming the energy they desire[11].

Table 2. Marshallian own-price and expenditure elasticities

	Food	Gasoline	LPG	Electricity	Other non-durables
Unconditional demand system					
Own-price	-0.907***	-0.481***	-0.476***	-0.672***	-1.804***
Expenditure	0.622***	1.774***	0.889***	0.271***	1.702***
Conditional on owning a vehicle					
Own-price	-0.840***	-0.557***	-0.408***	-0.671***	-1.498***
Expenditure	0.600***	1.337***	0.818***	1.133***	1.481***
Conditional on not owning a vehicle					
Own-price	-0.950***	-	-0.663***	-0.713***	-2.220***
Expenditure	0.590***	-	0.963***	1.172***	1.883***

Note: *** indicates significance at 1 percent.
Source: Own calculations

4. Simulation

4.1. Procedure

Our simulation procedure is as follows: First, we calculate the new shares in 2018 using the parameters obtained from the estimation of the conditional model and the new prices. With the new expenditure shares, if we assume total expenditure on durable goods remains unchanged, we obtain the new expenditures on the different goods considered. Dividing the expenditure shares on the different energy products before and after the reform by their average price in 2018 we obtain the consumption before and after the reform, which allows us to evaluate their impact on energy consumption and associated emissions (using the emission factors), as well as the additional revenue generated by the reform.

We would also be interested in providing some welfare measure arising from the reforms. Despite the various conceptual drawbacks fully described in Banks et al. (1996), the change in household welfare is quantified through the equivalent gain, a money-metric impact of price changes and/or

[11] In this sense, Ortega and Medlock (2021) estimate the demand for various energy products in Mexico by household income level, obtaining higher income elasticities for poorer households.

income changes. An equivalent gain (loss) is the amount of money that needs to be subtracted from (given to) the household to attain the pre-reform level of utility at final prices. We follow the method of King (1983) in computing this measure, although adapting it to the QAIDS, in a similar way to Thomas (2022). In this sense, we evaluate the equivalent loss (gain) for the case of a price change as:

$$EL^h = c(u_0, \boldsymbol{p^0}) - c(u_0, \boldsymbol{p^1}) \qquad [4]$$

where u_0 is pre-reform utility, p^0 and p^1 are the vector of pre- and post-reform prices, respectively, $\mathrm{c}(\mathrm{u}_0, \mathrm{p}^0)$ the observed pre-shock expenditure and $\mathrm{c}(\mathrm{u}_0, \mathrm{p}^1)$ the equivalent income, i.e., the expenditure level at pre-reform prices that is equivalent in utility terms to household expenditure at final prices. We calculate it from the expenditure function [1], using the parameters estimated in the conditional QUAIDS and the prices before and after the reform. The level of utility before the reform is calculated in [2] using the prices before the reform. Finally, to see the net distributional impact of the reforms we consider the index of Reynolds and Smolensky (1977).

4.2. Alternative scenarios

We consider several scenarios for simulation based on the introduction of a carbon tax. We introduce a CO_2 emissions tax on energy products covered by our model, using two alternatives, a tax rate of \$25/tCO_2 and a tax rate of \$50/tCO_2. To calculate the tax rates on each of the energy products we use the emission factors from INECC (2014) for gasoline and LPG, and CRE (2019) for electricity, as well as the OECD exchange rate (2022), to express the tax rates in Mexican pesos. Table 3 summarizes the different alternatives.

Table 3. Alternative scenarios

Energy product	CO_2 tax	
	REFORM 1 **25 \$/tCO_2**	**REFORM 2** **50\$/tCO_2**
Gasoline	1.157 pesos/l	2.314 pesos/l
Electricity	262 pesos/MWh	525 pesos/MWh
LPG	1.495 pesos/kg	2.989 pesos/kg

Source: Own calculations

We consider 2018 prices of magna and premium gasoline from IEA (2019), as well as the price of

LPG from SENER (2019), on which we apply the tax considered to obtain the corresponding price increase because of the reform, assuming full-pass-through to consumers. The results are presented in Table 4. In the case of residential electricity, as noted above, Mexican tariffs are heavily subsidized, so it is unrealistic to assume that the new tax on electricity will be fully passed on to consumers, so we assume that the 25(50) $/tCO_2$ tax will increase the residential price of electricity by 10(20) percent[12].

Since our proposed reforms generate additional tax revenue, we use it to reduce poverty and inequality. To do so, we consider two compensatory schemes: a lump-sum transfer to all households (Transfer 1) and a lump-sum transfer targeted only to the poorest households (defined as those in the bottom three deciles of income, Transfer 2).

Table 4. Price impact of different alternatives (percent of variation)

Energy product	CO_2 tax	
	REFORM 1 25 $/tCO_2$	REFORM 2 50$/tCO_2$
Gasoline	5.73	12.13
Electricity	10.00	20.00
LPG	10.49	22.17

Source: Own calculations

4.3. Results of simulation 1

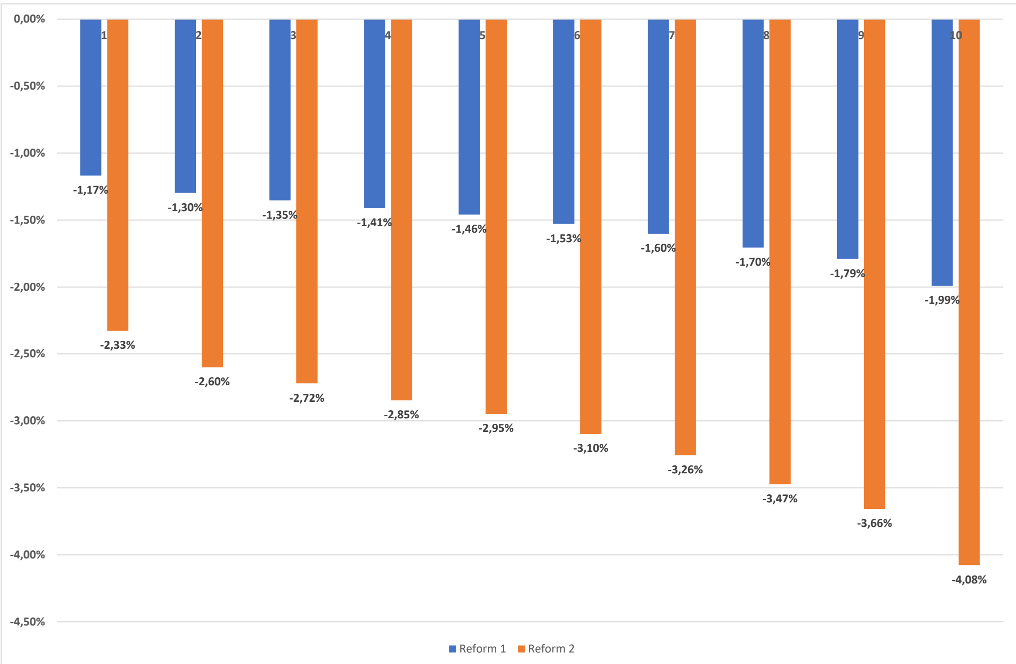
The introduction of a $25/tCO2 tax on energy products would reduce their demand 5.10 percent, with associated CO_2 emissions reduction of 3.52 percent. The additional revenue obtained would be 27,800 million pesos. In terms of welfare effects, the reform would lead to an average equivalent loss of 1.53 percent, and it has a progressive impact, with the equivalent gain decreasing as the income rises (or equivalent loss increasing with income, Figure 2). This result is because the progressive impact of the increase in the price of gasoline more than offsets the regressive impact derived from the increase in the price of electricity. Thus, if we consider the effect of the reform on each of the energy products separately (Table B4 in Annex B), we see that the increase in the price of electricity has a clearly regressive impact, with the average equivalent gain increasing with

[12] Renner et al. (2018) used data for 2014, and they estimate a 9 percent increase in price of residential electricity with a tax of $25/tCO_2$.

income, while the increase in the price of gasoline has a progressive effect, since wealthy households are more likely to own a car (see Table A3 in Annex A) and, also to consume more at the intensive margin. On the other hand, the impact of the price of LPG is progressive in the lower income deciles and regressive in the higher income deciles, because average LPG expenditure shares are increasing in the lower income deciles and decreasing in the higher income deciles.

Although the reform affects richer households more, it also harms some poor households, which see their energy costs increase, so the net distributional effect of the reform is unclear. Furthermore, the reform would increase the poverty rate (Figures 3 and 4), except in the south, where it would be very slightly reduced, as well as inequality, both at the national level and in each of the different areas considered (Table 5). So, these results justify the need to introduce compensatory schemes.

Figure 2. Equivalent gain per income decile

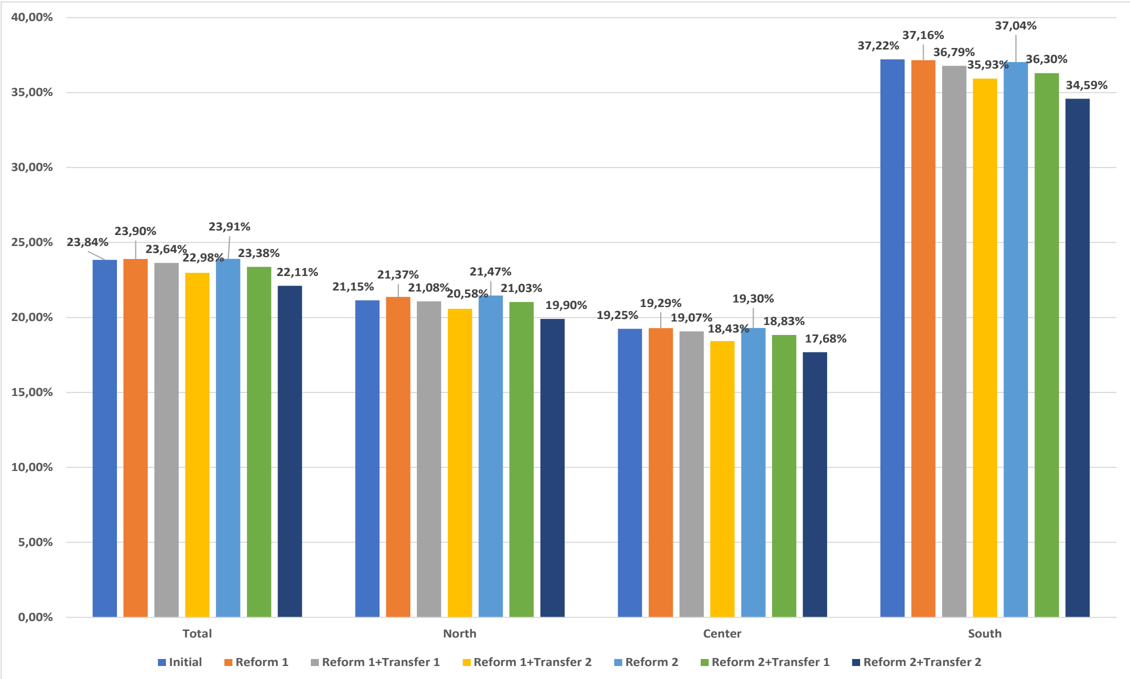


Note. Equivalent gain is defined as the percent of total non-durable expenditure.
Source: Own calculations

If the additional revenue is used to compensate all households through a lump sum transfer, each household would receive an annual amount of 888 pesos. This scheme would reduce inequality and the poverty rate with respect to the situation before the reform, both at the aggregate level and in the different areas considered. However, we can see that average reductions are not very large.

On the other hand, if we introduce the scheme to compensate households in the three bottom deciles of income, each household will receive 2958 pesos per year and the measure would make it possible to achieve greater reductions in inequality and in the poverty rate. In both cases the Reynolds-Smolensky index would become positive (0.0024 and 0.0067, respectively), so that the compensatory package converts a regressive into a net progressive reform, while at the same time reducing inequality and poverty (Figures 3 and 4 for geographical area and urban-rural divide respectively, and Table 5).

Figure 3. Poverty rate by geographical area



Source: Own calculations

Table 5. Gini index

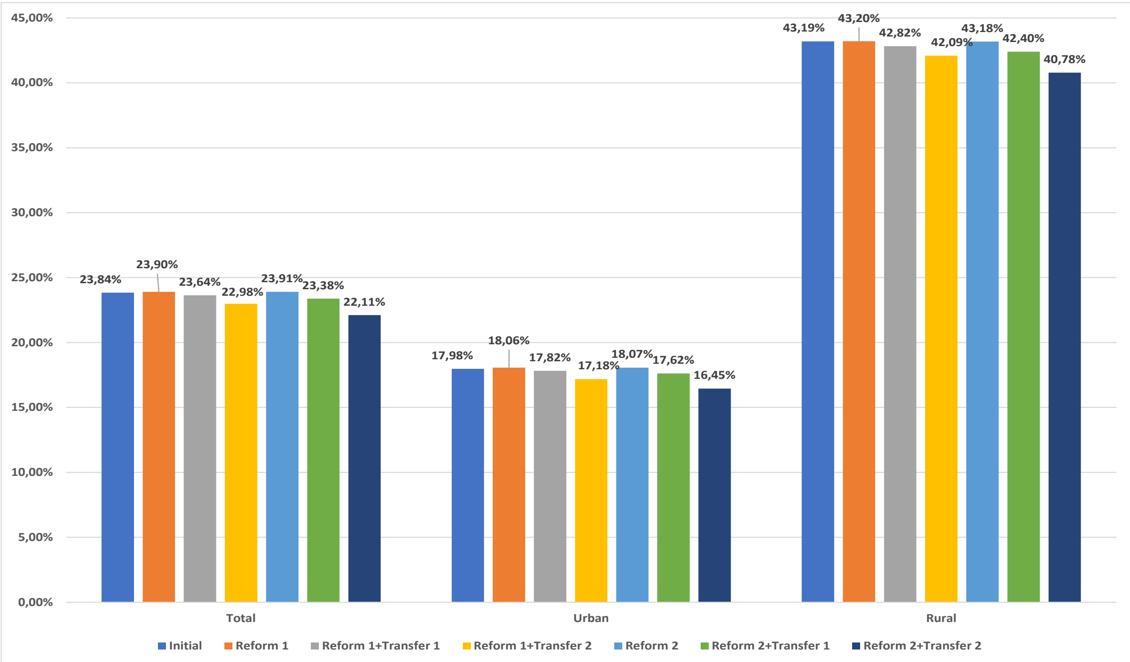
	Total	North	Center	South	Urban	Rural
Initial	0.3711	0.3618	0.3594	0.3881	0.3547	0.3686
Reform 1						
No compensation	0.3716	0.3625	0.3599	0.3884	0.3552	0.3688
Transfer to all households	0.3688	0.3598	0.3573	0.3846	0.3527	0.3646
Transfer to households in the three bottom deciles	0.3644	0.3564	0.3540	0.3767	0.3496	0.3548
Reform 2						
No compensation	0.3721	0.3631	0.3604	0.3886	0.3557	0.3689
Transfer to all households	0.3665	0.3579	0.3554	0.3813	0.3509	0.3608
Transfer to households in the three bottom deciles	0.3582	0.3513	0.3490	0.3662	0.3449	0.3421

Source: Own calculations

4.4. Results of simulation 2

If instead of a carbon tax of \$25/tCO_2, we double the rate to \$50/tCO_2, the demand for the energy products considered would fall by 11.33 percent and the associated CO_2 emissions by 9.74 percent, generating an excess revenue of 54026 million pesos. The welfare impacts (Figure 2) would be as expected of greater magnitude than in the previous simulation, with an average equivalent loss of -3.10 percent, although they would also be progressive, with an equivalent gain decreasing with income, due, once again, to the progressive impact of the increase in the price of gasoline, which offsets the regressive impact of the increase in the price of electricity (see Table B5 in Annex B).

Figure 4. Poverty rate by urban-rural divide



Source: Own calculations

Anyway, this reform would also have a net regressive distributive effect (Reynolds-Smolensky of -0.0009) and would increase the poverty rate (except in the south, where it is slightly reduced, and in rural areas, where it hardly varies), increasing inequality in each of the areas considered to a greater extent than with Reform 1 (Figures 3-4 and Table 5), which justifies the application of a compensatory scheme here as well. In the same scenarios as before for the transfer schemes, now a lump-sum transfer to all households spending all additional revenue represents each household would receive 1725.6 pesos per year, while if the transfer is targeted only to households in the three bottom income deciles, each household would receive 5751.8 pesos per year. Again, with the compensatory schemes (and as before especially the second compensatory package) the reform would contribute to reduce inequality and poverty (Figures 3-4 and Table 5), with a progressive net distributional impact (the Reynolds-Smolensky index with the compensations would be 0.0046 and 0.0129, respectively).

5. Summary and conclusions

This paper analyzes the effects on households of a carbon tax on energy products in Mexico trying to achieve significant reductions in CO_2 emissions associated with domestic energy consumption. First, we estimate a complete demand system for Mexican households, then we use the results to simulate the revenue and distributional effects of the application of a carbon tax with in two scenarios \$25 and \$50/tCO2. Then, we propose to use the additional revenue generated to compensate households for the negative impacts of the reform.

The results show that the reforms considered would reduce energy consumption and associated emissions, and would also have a progressive impact on welfare, affecting richer households more, because of the progressive effect of the gasoline tax, which offsets the regressive impact of the electricity tax. In any case, the reforms, by increasing the energy expenditure of poor households, would increase poverty and inequality in Mexico. The use of the revenue generated through lump-sum transfers, especially if these are targeted to the poorest households, would reduce inequality and poverty relative to the baseline situation without reform, making the reforms with compensatory packages have a net progressive distributional impact.

Therefore, the implementation of a carbon tax on energy goods with properly defined compensation schemes would achieve reductions in energy consumption and associated CO2 emissions of households, contributing to meet the Mexican commitments derived from the Paris agreement, while at the same time reducing inequality and poverty.

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Annex A. Data description

Table A1. Descriptive statistics of main variables

	Observations	Mean	Standard deviation	Minimum	Maximum
Food share	230295	0.5344	0.1788	0.0020	1
Magna gasoline share	230295	0.0775	0.1234	0	0.9894
Premium gasoline share	230295	0.0076	0.0459	0	0.8229
LPG share	230295	0.0410	0.0567	0	0.7865
Electricity share	230295	0.0507	0.0599	0	0.9301
Other non-durable goods share	230295	0.2888	0.1364	0	0.9955
Gasoline share	230295	0.0851	0.1278	0	0.9894
Food price	230295	0.8337	0.1673	0.4792	1.0468
Magna gasoline price	230295	0.7294	0.2306	0.3474	1.0793
Premium gasoline price	230295	0.7213	0.2492	0.3386	1.0865
LPG price	230295	0.7439	0.2092	0.3949	1.0968
Electricity price	230295	1.0584	0.3357	0.5533	2.9848
Other non-durable goods price	230295	0.8577	0.1420	0.4288	1.1123
Gasoline price	230295	0.7265	0.2367	0.3397	1.0865
Total expenditure on non-durables	230295	12429.10	7454.99	1497.42	44821.69
Income	230295	36954.51	28754.24	4065.05	182587.4
Gender	230295	0.2593	0.4382	0	1
Age	230295	48.7931	15.6677	12	110
Members ≥12 years	230295	2.9560	1.4244	1	33
Members <12 years	230295	0.8615	1.0809	0	13
Urban	230295	0.6784	0.4671	0	1
Rural	230295	0.3216	0.4671	0	1
North	230295	0.3175	0.4655	0	1
Center	230295	0.4399	0.4964	0	1
South	230295	0.2426	0.4287	0	1
Less than primary education	230295	0.2660	0.4419	0	1
Primary education	230295	0.2307	0.4213	0	1
Secondary education	230295	0.4013	0.4902	0	1
Higher education	230295	0.1021	0.3027	0	1
Number of rooms	230295	3.7005	1.5414	0	23
Rented housing	230295	0.1268	0.3327	0	1
Owned house with mortgage	230295	0.0834	0.2765	0	1
Owned house without mortgage	230295	0.6332	0.4819	0	1
Dwelling in other situation	230295	0.1567	0.3635	0	1
Van	230295	0.1160	0.3202	0	1
Car	230295	0.2703	0.4441	0	1
Radio recorder	230295	0.2002	0.4002	0	1
Radio	230295	0.2039	0.4029	0	1
TV	230295	0.9295	0.2560	0	1
Videotape player	230295	0.0855	0.2796	0	1
Blender	230295	0.8548	0.3523	0	1
Microwave	230295	0.4189	0.4934	0	1
Refrigerator	230295	0.8576	0.3494	0	1
Stove	230295	0.8905	0.3122	0	1
Washing machine	230295	0.6589	0.4741	0	1
Iron	230295	0.7803	0.4141	0	1
Fan	230295	0.5495	0.4975	0	1
Vacuum cleaner	230295	0.0640	0.2447	0	1
Computer	230295	0.2372	0.4254	0	1
Vehicle	230295	0.4793	0.4996	0	1

Definition of variables:

- Geographical area:
  - North (Baja California, Baja California Sur, Coahuila de Zaragoza, Chihuahua, Durango, Nuevo León, Sinaloa, Sonora, Tamaulipas, Zacatecas)
  - Centre (Aguascalientes, Colima, DF, Guanajuato, Hidalgo, Jalisco, México, Michoacán, Morelos, Nayarit, Puebla, Querétaro, San Luis Potosí, Tlaxcala)
  - South (Campeche, Chiapas, Guerrero, Oaxaca, Quintana Roo, Tabasco, Veracruz de Ignacio de la Llave, Yucatán)
- Area of residence:
  - urban (municipality ≥ 2500 inhabitants)
  - rural (municipality < 2500 inhabitants)
- Quarterly household income
- Gender of household head: female (gender=1), male (gender=0)
- Age of household head
- Level of education of household head: Less than primary education, primary education, secondary education, higher education
- Number of household members ≥12 years
- Number of household members <12 years
- Number of rooms in the dwelling
- Housing tenure: rented, owned with mortgage, owned without mortgage, other situation
- Ownership of car, van, radio recorder, radio, television, videotape player, blender, microwave, refrigerator, stove, washing machine, iron, fan, vacuum cleaner, computer, vehicle (car, van, pickup and/or motorbike).

Comparison of samples by type of gasoline demand

Table A2. Differences in samples by type of gasoline consumption

	Magna gasoline consumers	Premium gasoline consumers
Real income	56541.17	79502.37
Real expenditure on non-durables	18763.66	22231.6
Gender (female=1)	0.1796	0.2102
Age of head of household	47.9586	48.1070
Members ≥12 years	3.1277	2.8565
Members <12 years	0.8573	0.7044
Urban	0.7028	0.8141
North	0.4161	0.3672
Center	0.4113	0.4189
South	0.1725	0.2140
Below primary school	0.1746	0.1075
Primary education	0.2021	0.1400
Secondary education	0.4555	0.4160
Higher education	0.1678	0.3365

Source: Own calculations

Households that consume premium gasoline have on average higher incomes and expenditures on non-durables, a lower number of members (both older and younger), a higher percentage of female-headed households, of households living in urban areas, of households living in the south (and a lower percentage of households living in the north) and of households in which the head has higher education (and a lower percentage of households with less than primary, elementary or secondary education). More than half of the households that consume premium gasoline belong to the two highest income and expenditure deciles.

Comparison of samples by ownership of vehicles

Table A3. Differences in samples by vehicle ownership

	With vehicle	Without vehicle
Real income	56662.24	30840.98
Real expenditure on non-durables	18321.7	10911.75
Gender (female=1)	0.1845	0.3281
Age of head of household	48.2813	49.2641
Members ≥12 years	3.1093	2.8150
Members <12 years	0.8404	0.8810
Urban	0.7063	0.6528
North	0.4041	0.2378
Center	0.4213	0.4570
South	0.1747	0.3052
Below primary school	0.1797	0.3454
Primary education	0.2032	0.2559
Secondary education	0.4468	0.3594
Higher education	0.1703	0.0393

Source: Own calculations

Households with vehicles have higher average incomes and expenditures on non-durables, a higher number of older members (but fewer younger members), a higher percentage of male-headed households, of households living in urban areas, of households living in the north (and a lower percentage of households living in the south), and of households in which the head has higher or secondary education (and a lower percentage of households with less than primary or elementary education).

More than half of the households without a vehicle belong to the first four deciles of income or expenditure on non-durables, while households with a vehicle belonging to the first four deciles account for just over 20% of these households. Therefore, we can assume that households without vehicles, mostly poor households, have higher price elasticities because their consumption is so tight that they must reduce their consumption in the face of any price increase. On the other hand, their income elasticity is lower because they cannot do anything about a marginal increase in their income and would need a significant increase in income to be able to change their consumption.

Annex B. Estimation and simulation results

Table B1. Unconditional QUAIDS estimates

	Food	Gasoline	LPG	Electricity	Other non-durables
Log price food	-0.1088***	-0.0106*	0.0016	-0.0476***	0.1655***
Log price gasoline	-0.0106**	0.0427***	-0.0139***	-0.0185***	0.0003
Log price LPG	0.0016	-0.0139***	0.0224***	0.0029**	-0.0130***
Log price electricity	-0.0476***	-0.0185***	0.0029***	0.0134***	0.0499***
Log price other non-durables	0.1655***	0.0003	-0.0130***	0.0499***	-0.2027***
Log expenditure	-0.1672***	0.0853***	0.0123***	-0.0657***	0.1354***
Log expenditure^2	-0.0125***	-0.0061***	-0.0058***	0.0066***	0.0179***
IV total expenditure	0.2471***	-0.0546***	-0.0063***	0.0226***	-0.2089***
Gender	-0.0078***	-0.0129***	0.0024***	0.0028***	0.0156***
Age	0.0029***	0.0001*	0.0001***	0.0004***	-0.0036***
Age^2	-0.0000***	-0.0000***	0.0000***	-0.0000***	0.0000***
Members ≥ 12 years	0.0327***	-0.0113***	-0.0007***	0.0020***	-0.0227***
Member < 12 years	0.0252***	-0.0088***	-0.0013***	0.0022***	-0.0173***
Urban	0.0215***	-0.0213***	0.0007**	0.0110***	-0.0118***
North	-0.0906***	0.0253***	0.0085***	0.0261***	0.0308***
Center	-0.0078***	-0.0045***	0.0119***	-0.0017***	0.0021**
Less than primary education	-0.0052***	-0.0150***	0.0003	0.0004	0.0194***
Primary education	0.0026	-0.0203***	0.0013***	0.0009*	0.0155***
Secondary education	0.0116***	-0.0212***	0.0005	-0.0006	0.0096***
Number of rooms	-0.0005	0.0009***	0.0009***	0.0013***	-0.0026***
Rented house	-0.0075***	0.0023***	-0.0018***	-0.0026***	0.0095***
Owned house with mortgage	-0.0066***	0.0077***	-0.0062***	-0.0012**	0.0064***
Owner house without mortgage	0.0048***	0.0026***	-0.0010***	0.0017***	-0.0082***
Van	-0.0260***	0.0903***	-0.0035***	0.0016***	-0.0625***
Car	-0.0303***	0.1084***	-0.0058***	-0.0002	-0.0721***
Radio recorder	0.0032***	-0.0052***	0.0008***	0.0008***	0.0004
Radio	-0.0006	-0.0022***	0.0010***	0.0010***	0.0007
TV	0.0124***	0.0039***	0.0016***	0.0057***	-0.0158***
Videotape player	0.0074***	-0.0097***	0.0016***	0.0039***	-0.0032**
Blender	0.0241***	-0.0035***	0.0050***	0.0007*	-0.0263***
Microwave	-0.0010	0.0044***	-0.0008***	0.0025***	-0.0051***
Refrigerator	0.0023	-0.0008	0.0015***	0.0080***	-0.0110***
Stove	0.0097***	-0.0090***	0.0340***	0.0065***	-0.0412***
Washing machine	0.0098***	0.0011**	0.0005*	0.0012***	-0.0125***
Iron	0.0152***	-0.0026***	0.0018***	0.0013***	-0.0157***
Fan	-0.0023**	-0.0013***	-0.0103***	0.0098***	0.0041***
Vacuum cleaner	0.0095***	-0.0004	-0.0009*	0.0039***	-0.0121***
Computer	0.0163***	0.0042***	-0.0011***	0.0004	-0.0197***
Constant	0.5774***	0.0283***	-0.0131***	0.0657***	0.3417***

Note: ***, **, * report significance at 1%, 5% and 10%, respectively.
Source: Own calculations

Table B2. Conditional QUAIDS estimates (owners)

	Food	Gasoline	LPG	Electricity	Other non-durables
Log price food	-0.0563***	-0.0303***	0.0068*	-0.0247***	0.1044***
Log price gasoline	-0.0303***	0.0778***	-0.0183***	-0.0225***	-0.0068
Log price LPG	0.0068	-0.0183***	0.0232***	0.0007	-0.0125***
Log price electricity	-0.0247***	-0.0225***	0.0007	0.0181***	0.0284***
Log price other non-durables	0.1044***	-0.0068	-0.0125***	0.0284***	-0.1136***
Log expenditure	-0.1295***	0.0951***	0.0099***	-0.0243***	0.0487***
Log expenditure^2	-0.0160***	-0.0101***	-0.0049***	0.0090***	0.0220***
IV total expenditure	0.2264***	-0.0602***	-0.0049***	-0.0265***	-0.1349***
Gender	-0.0181***	0.0122***	-0.0000	-0.0105***	0.0164***
Age	0.0035***	-0.0012***	0.0003***	0.0008***	-0.0034***
Age^2	-0.0000***	0.0000***	0.0000	-0.0000***	0.0000***
Members ≥ 12 years	0.0303***	-0.0149***	0.0000	-0.0021***	-0.0133***
Member < 12 years	0.0246***	-0.0149***	-0.0004**	-0.0006***	-0.0087***
Urban	0.0166***	0.0005	-0.0028***	-0.0027***	-0.0116***
North	-0.0776***	0.0234***	0.0071***	0.0377***	0.0093***
Center	-0.0009	-0.0042***	0.0098***	-0.0030***	-0.0016
Less than primary education	-0.0098***	-0.0095***	0.0003	-0.0077***	0.0268***
Primary education	-0.0011	-0.0157***	0.0017***	-0.0054***	0.0205***
Secondary education	0.0081***	-0.0158***	-0.0001	-0.0045***	0.0122***
Number of rooms	0.0021***	-0.0030***	0.0013***	0.0033***	-0.0038***
Rented house	-0.0099***	0.0137***	-0.0016***	-0.0038***	0.0016
Owned house with mortgage	-0.0056**	0.0084***	-0.0050***	0.0022***	0.0001
Owner house without mortgage	0.0077***	-0.0104***	-0.0001	0.0086***	-0.0058***
Radio recorder	0.0058***	-0.0037***	0.0007*	-0.0024***	-0.0003
Radio	0.0019	-0.0035***	0.0017***	0.0003	-0.0003
TV	0.0173***	-0.0193***	-0.0011	0.0078***	-0.0047*
Videotape player	0.0056***	-0.0070***	0.0017***	0.0011*	-0.0013
Blender	0.0254***	-0.0136***	0.0043***	0.0019***	-0.0180***
Microwave	-0.0002	-0.0018*	0.0001	0.0077***	-0.0057***
Refrigerator	0.0089***	-0.0219***	0.0012	0.0162***	-0.0044**
Stove	0.0194***	-0.0239***	0.0257***	0.0109***	-0.0321***
Washing machine	0.0196***	-0.0207***	0.0013***	0.0101***	-0.0103***
Iron	0.0170***	-0.0072***	0.0017***	0.0002	-0.0118***
Fan	0.0034***	-0.0105***	-0.0091***	0.0122***	0.0040***
Vacuum cleaner	0.0096***	-0.0083***	-0.0008	0.0072***	-0.0077***
Computer	0.0168***	-0.0023**	-0.0011***	0.0054***	-0.0188***
Heckman's lambda	0.0333***	-0.0771***	0.0011	0.0559***	-0.0132***
Constant	0.4110***	0.3222***	-0.0135***	-0.0699***	0.3502***

Note: ***, **, * report significance at 1%, 5% and 10%, respectively.
Source: Own calculations

Table B3. Conditional QUAIDS estimates (non-owners)

	Food	GLP	Electricity	Other non-durables
Log price food	-0.3142***	-0.0298***	-0.0595***	0.4034***
Log price LPG	-0.0298***	-0.0142***	0.0063***	0.0377***
Log price electricity	-0.0595***	0.0063***	0.0212***	0.0320***
Log price other non-durables	0.4034***	0.0377***	0.0320***	-0.4731***
Log expenditure	0.0186	0.0987***	-0.0137***	-0.1035***
Log expenditure²	-0.0214***	-0.0080***	0.0021***	0.0273***
IV total expenditure	0.3135***	-0.0077***	-0.0392***	-0.2666***
Gender	0.0103***	0.0037***	-0.0212***	0.0073**
Age	0.0020***	0.0000	0.0012***	-0.0032***
Age²	0.0000***	0.0000***	-0.0000***	0.0000***
Members ≥ 12 years	0.0389***	-0.0014***	-0.0038***	-0.0338***
Member < 12 years	0.0281***	-0.0018***	-0.0017***	-0.0246***
Urban	0.0292***	0.0030***	-0.0071***	-0.0251***
North	-0.1171***	0.0081***	0.0509***	0.0582***
Center	-0.0185***	0.0120***	0.0092***	-0.0026
Less than primary education	0.0177***	0.0023*	-0.0112***	-0.0087**
Primary education	0.0225***	0.0026**	-0.0100***	-0.0151***
Secondary education	0.0288***	0.0021**	-0.0085***	-0.0225***
Number of rooms	-0.0050***	0.0004**	0.0053***	-0.0008
Rented house	-0.0044**	-0.0021***	-0.0069***	0.0134***
Owned house with mortgage	-0.0107***	-0.0072***	0.0046***	0.0134***
Owner house without mortgage	-0.0008	-0.0011*	0.0093***	-0.0073***
Radio recorder	0.0015	0.0012**	-0.0032***	0.0005
Radio	-0.0038**	0.0006	0.0008**	0.0024*
TV	0.0097***	0.0019***	0.0085***	-0.0201***
Videotape player	0.0106***	0.0018**	-0.0021***	-0.0103***
Blender	0.0229***	0.0049***	0.0018***	-0.0295***
Microwave	-0.0040**	-0.0014***	0.0090***	-0.0037**
Refrigerator	-0.0023	0.0010	0.0188***	-0.0175***
Stove	0.0103***	0.0351***	0.0073***	-0.0527***
Washing machine	0.0020	0.0001	0.0117***	-0.0138***
Iron	0.0169***	0.0020***	0.0004	-0.0193***
Fan	-0.0069***	-0.0115***	0.0127***	0.0057***
Vacuum cleaner	-0.0061	-0.0035**	0.0155***	-0.0059
Computer	0.0104***	-0.0012*	0.0073***	-0.0165***
Heckman's lambda	0.0570***	0.0027	-0.0589***	-0.0008
Constant	1.1100***	-0.3036***	-0.0172	0.2108***

Note: ***, **, * report significance at 1%, 5% and 10%, respectively.
Source: Own calculations

Table B4. Equivalent gain (Reform 1). Impact by energy good

	ELECTRICITY		GASOLINE				LPG			
			Whole sample		Households with vehicle		Whole sample		Households with positive spending in LPG	
	Equivalent gain	% losers	Equivalent gain	% losers	Equivalent gain	% losers	Equivalent ga	% losers	Equivalent gain	% losers
Total	-0.57	99.7	-0.50	47.5	-1.09	99.9	-0.46	98.2	-0.50	99.8
Income deciles										
1	-0.72	100	-0.05	10.9	-0.50	97.9	-0.39	90.6	-0.54	99.6
2	-0.67	99.9	-0.14	20.5	-0.71	99.9	-0.48	97.4	-0.57	99.9
3	-0.63	99.9	-0.22	27.4	-0.82	100	-0.50	98.5	-0.57	99.7
4	-0.60	99.7	-0.31	36.3	-0.88	100	-0.50	99.0	-0.54	99.9
5	-0.58	99.8	-0.39	41.7	-0.95	100	-0.49	99.2	-0.53	99.9
6	-0.55	99.7	-0.49	49.1	-1.01	100	-0.49	99.3	-0.52	99.9
7	-0.52	99.6	-0.61	57.7	-1.07	100	-0.47	99.3	-0.50	99.9
8	-0.49	99.2	-0.76	67.5	-1.14	100	-0.46	99.4	-0.47	99.7
9	-0.46	99.7	-0.90	75.8	-1.20	100	-0.43	99.6	-0.45	99.9
10	-0.46	99.6	-1.15	88.0	-1.31	100	-0.39	99.5	-0.40	99.8

Notes:
Equivalent loss is expressed as a percentage of total expenditure on non-durables.
Losers: Equivalent loss<0
For each energy product the equivalent gain is calculated assuming that the reform only affects the price of the energy product considered.
Source: Own calculations

Table B5. Equivalent gain (Reform 2). Impact by energy good

	ELECTRICITY		GASOLINE				LPG			
			Whole sample		Households with vehicle		Whole sample		Households with positive spending in LPG	
	Equivalent gain	% losers	Equivalent gain	% losers	Equivalent gain	% losers	Equivalent ga	% losers	Equivalent gain	% losers
Total	-1.11	99.8	-1.06	47.5	-2.28	99.9	-0.95	98.4	-1.03	99.8
Income deciles										
1	-1.39	100	-0.11	10.9	-1.05	98.4	-0.81	91.1	-1.11	99.6
2	-1.30	99.9	-0.30	20.5	-1.49	99.9	-0.99	97.7	-1.16	99.9
3	-1.23	99.9	-0.46	27.4	-1.72	100	-1.03	98.6	-1.16	99.7
4	-1.17	99.7	-0.66	36.3	-1.86	100	-1.03	99.1	-1.11	99.9
5	-1.12	99.8	-0.82	41.7	-1.99	100	-1.01	99.3	-1.09	99.9
6	-1.07	99.8	-1.03	49.1	-2.12	100	-1.01	99.5	-1.07	99.9
7	-1.02	99.6	-1.28	57.7	-2.24	100	-0.98	99.4	-1.03	99.9
8	-0.96	99.2	-1.60	67.5	-2.38	100	-0.94	99.6	-0.98	99.9
9	-0.91	99.8	-1.89	75.8	-2.51	100	-0.89	99.6	-0.92	99.9
10	-0.91	99.8	-2.40	88.0	-2.74	100	-0.80	99.6	-0.82	99.8

Notes:
Equivalent loss is expressed as a percentage of total expenditure on non-durables.
Losers: Equivalent loss<0
For each energy product the equivalent gain is calculated assuming that the reform only affects the price of the energy product considered.
Source: Own calculations