Vulnerability of fuel poor to energy price increases from carbon taxation: A microsimulation study for the Austrian Province of Styria

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Abstract

Major efforts and a comprehensive mix of policy instruments are needed for the transition to carbon neutrality, including efficiency-improvement measures, command-and-control policies, and carbon pricing. The implementation of these policy instruments is expected to raise energy prices and related service costs considerably in the medium to long-term, with the burden unequally distributed among households and population segments. In the present paper, we analyze the short-run impacts of a national carbon tax for heating and motor fuels and of five accompanying revenue recycling schemes on different types of households and regions in the Austrian Province of Styria, using the EASI demand system. The effects of carbon tax and compensation schemes are assessed in terms of welfare, equality and emissions. Besides regional differences, we focus on the welfare impacts for particularly vulnerable households, for whose identification different measures of energy and fuel poverty from the literature are applied. We find that households in rural areas are more affected by carbon pricing than households in urban areas, amongst others due to a higher dependence on the car and a higher share of fossil-based heating systems. For households classified as energy or fuel poor under the definitions considered, carbon tax impacts are up to two times higher than for the average Styrian household, and up to 2.2 times higher if they additionally live in rural areas. Compensation schemes that differentiate between vulnerable and non-vulnerable households (target-based) or between low and high-income households (income-based) effectively reduce negative welfare effects from the carbon tax for the most vulnerable ones as well as pre-tax income inequality, while emission reduction is almost as high as without compensation.

Keywords: Demand system; Carbon taxation; Fuel poverty; Tax revenue recycling;

1 Introduction

Major efforts are needed to reach the climate targets of the EU and Austria. With the 'Fit for 55' package, the EU aims at reducing greenhouse gas emissions by at least 55% until 2030, while Austria wants to become climate neutral by 2040 the latest. Achieving these targets requires a comprehensive mix of policy instruments, including efficiency-improvement measures, command-and-control policies, and carbon pricing.

Carbon pricing is reflected in the globally increasing implementation of carbon taxation, Austria's national (fixed-price) emissions trading system for mobility and heating that started in October 2022, or the European Commission's proposal to introduce an emissions trading system for these sectors in 2026. The implementation of these policy instruments is expected to raise energy prices and related service costs considerably in the medium to long-term, with the burden unequally distributed among households and population segments since starting point and options for action to reduce emissions differ considerably. Recent studies on the effects of carbon pricing highlight that especially housing attributes (e.g. age of the building, installed heating system, ownership), mobility behaviour (e.g. share of motorised private transport and lacking alternatives in rural regions), and socio-demographic attributes (e.g. household size, income) influence a household's energy consumption and therefore vulnerability to policies restricting individual carbon emissions (Budgetdienst, 2019; Eisner et al., 2021). For instance, in industrialized countries, more affluent households consume energy and generate emissions to a much higher degree than poor ones who use coping strategies cutting back on energy consumption to keep their energy bills manageable (Berry, 2019; Eisfeld and Seebauer, 2022; Smetschka et al., 2019; Theine et al., 2022; Tovar Reaños and Wölfing, 2018). Households owning a car, living in rural areas or in rent, and relying on fossil fuel-based heating systems are disproportionally more affected by climate policies such as carbon pricing (Budgetdienst, 2019; Eisner et al., 2021; Tovar Reaños and Wölfing, 2018). In addition, impacts differ depending on the considered energy good. A price increase in motor fuels mainly affects middle-income households (Berry, 2019; Tiezzi, 2005), while a price increase in electricity and heating affects poor households the most and shows a highly regressive nature (Kirchner et al., 2019; Renner et al., 2019; Tovar Reaños and Wölfing, 2018). Only a few studies (Eisner et al., 2021; Renner et al., 2019, 2018) cover all areas of household energy consumption (i.e.

electricity, heating and motor fuels) and underscore that distributional and welfare effects of climate policy induced changes in energy prices strongly differ between consumption goods and population segments.

For socially disadvantaged or vulnerable households, the issue of carbon-neutral transformation is usually rather complex. Typically, these households lack the capacity and resources to shift their consumption to less carbon-intensive products and services, for example, by moving to more energy-efficient homes, purchasing energy-efficient household appliances, or buying electric vehicles. To the best of our knowledge a comprehensive exploration of specific vulnerable groups and the respective welfare and distributional impacts of policy induced changes in energy costs, e.g. due to a carbon tax, as well as their regional implications has not yet been conducted. Additionally, most studies focus solely on distributional effects and welfare, thus ignoring the complex interrelation between vulnerability and carbon policy. Notable exceptions are Renner et al. (2019, 2018) and van der Ploeg et al. (2022), who assess welfare and emission impacts of carbon taxes.

In the present paper, we aim to address the above raised issues on the example of the Austrian Province of Styria. More precisely, we analyze the impacts of a carbon tax and several compensation schemes on different types of households and regions and identify degree and cause of arising differences. In order to explore the sensitivity of households to climate policy in more detail, this paper links expenditure with CO_2 emissions and identifies the sensitivity to climate policy of deprived households based on multiple characteristics. Although we model the implementation of a nationwide carbon tax, all analyses are carried out for a particular province, since in Austria the concrete design of climate protection measures as well as accompanying measures (e.g. heating subsidies, housing subsidies, public transport services, etc.) often fall within the sphere of action of the provinces. The results of this study are intended to inform policy makers in designing a socially fair transformation in Styria.

2 Case study region

Styria is one of the nine federal provinces of Austria. With 1.25 million inhabitants (01.01.2022) and an area of 16 400 km² the province hosts 14% of Austria's total population and covers 20% of the nation (Statistics Austria, 2022). Thus, population density lies below the nation's average. The choice of Styria as case study region has been motivated by several facts. First of all, the province is very heterogeneous with urban centers on the one hand, such as the capital Graz where 23% of Styria's population lives and 38% of its employees work, and very rural regions on the other hand. This makes it an interesting region for studying differences in the impacts of a CO_2-tax on urban and rural households. Secondly, Styria ranks among those regions in Europe most heavily fragmented by human settlements and is not well served by public transport in many rural places. This causes a high car-dependency in many regions of the province. Thirdly, due to Styria's high share of rural areas where single-family homes are the predominant housing form, the share of households heating with oil – the heating fuel with the highest CO_{2eq} emission factor – lies above the nationwide average (Statistics Austria, 2021a).

3 Method

Methodologically, we build upon Eisner et al. (2021), who apply the Exact Affine Stone Index (EASI) demand system of Lewbel and Pendakur (2009) to Austria. In the present study, we extend the model of Eisner et al. (2021) threefold: First, we include the most recent wave of the Austrian Household Budget Survey (HBS), i.e. 2019/2020, provided by Statistics Austria (see section 4). Second, we use the bootstrap method to estimate standard errors of elasticities (see section 3.1). Third, we additionally simulate CO_2 emissions in order to evaluate emissions along with economic welfare and equality (see section 3.2).

3.1 *EASI demand system and estimation of standard errors*

As in Eisner et al. (2021), we use the EASI demand system of Lewbel and Pendakur (2009) for modelling consumer demand changes due to price changes. The key innovation of the EASI demand system over other demand systems, like the Almost Ideal Demand System (AIDS) and the more general Quadratic Almost Ideal Demand System (QUAIDS), is the accurate approximation of complex Engel curves (Lewbel and Pendakur, 2009), which show how the demand for a good is influenced by income. The EASI demand system with the budget shares (w_j) of each of the j goods has the following linear-in parameter form:

$$w_j = \sum_{r=0}^{5} b_{rj} y^r + \sum_{l=1}^{L} \left(C_{ij} z_l + D_{lj} z_l y \right) + \sum_{l=0}^{L} \sum_{k=1}^{J} A_{lkj} z_l p_k + \sum_{k=1}^{J} B_{kj} p_k y + \varepsilon_j.$$

where y is the implicit utility – also interpretable as a measure of log real expenditure – and given by

$$y = \frac{\left(\log(x) - \boldsymbol{p}'\boldsymbol{w} - \sum_{l=0}^{L} \frac{z_l \boldsymbol{p}' \boldsymbol{A}_l \boldsymbol{p}}{2} \right)}{1 - \frac{\boldsymbol{p}' \boldsymbol{B} \boldsymbol{p}}{2}}.$$

Further, z_l are household characteristics including $z_0 = 1$ the intercept, p_k are the log prices and x is the nominal total expenditure. There are the interaction terms of household characteristics and utility ($z_l y$), of household characteristics and log prices ($z_l p_k$), and of log prices and utility ($p_k y$). Finally, ε_j is an individual error term. As in Eisner et al. (2021), we use the iterative linear three stage least squares (3SLS) as proposed in Lewbel and Pendakur (2009). Finally, we use a small modification of the model where we set the interaction terms of log prices and utility ($p_k y$) to 0. For more details on the algebraic formulation see Eisner et al. (2021) and Lewbel and Pendakur (2009).

For the estimation of standard errors of elasticities, we apply a bootstrap method. Mizobuchi and Tanizaki (2014) use moving block bootstrap and pairs bootstrap to estimate elasticities in an Almost Ideal Demand System (AIDS). In this study, we draw on the pairs bootstrap, since the moving block bootstrap is primarily used for serial correlation, whereas in the data applied, households differ over the years. As in Mizobuchi and Tanizaki (2014), we use 10 000 bootstrap estimates for the calculation of the standard errors (estimated variance of the bootstrap). Advantages of using the bootstrap method include the additional calculation of compensated elasticities and the accurate calculation of in-group dependence for the error terms in the elasticities.

3.2 *Emissions*

CO_2 emissions are calculated from a demand-side perspective and comprise the CO_2 emissions resulting directly and indirectly in the household sector. Direct emissions result from the direct consumption of fuels by households and refer to the direct CO_2 content of each fuel. Indirect emissions, by contrast, arise from the direct and indirect energy use in the production process of goods consumed by households. This consumption-based approach follows Renner et al. (2018) and van der Ploeg et al. (2022).

Direct emissions, resulting from the direct consumption of fuels, are calculated based on expenditure data. More precisely, we use price per fuel unit data from national statistics (Statistics Austria, 2021b) and emission factors from the national inventory (Umweltbundesamt, 2021) to determine direct carbon intensities $CI_{dir}(tCO_2/EUR)$. Indirect carbon intensities and emissions are calculated by using an environmental input-output model (Kulmer et al., 2020) calibrated to EXIO database (Stadler et al., 2018). They comprise both, direct carbon emissions resulting from direct production emissions in the respective sector, and indirect carbon emissions caused by the release of carbon emissions in the production of intermediate inputs in the production process. Indirect carbon intensities are thus defined as:

$$\boldsymbol{CI}_{ind} = \boldsymbol{CI}'(\boldsymbol{I} - \boldsymbol{A})^{-1} \quad (1)$$

where $\boldsymbol{CI}$ is the direct carbon intensity of production and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ the Leontief inverse. The resulting indirect carbon intensities $CI_{ind}(tCO_2/EUR)$ contain all direct and indirect production emissions.

Total demand carbon intensities per sector are then:

$$\boldsymbol{CI} = \boldsymbol{CI}_{dir} + \boldsymbol{CI}_{ind} \quad (2)$$

Total CO_2 emissions embedded in household consumption, which represent the carbon footprints, are derived by multiplying expenditure per good with the respective carbon intensity CI (tCO_2/EUR).

3.3 *Indicators to measure distributional impacts*

To assess the distributional impacts of different carbon tax scenarios and revenue recycling schemes, we make use of several indicators, including various poverty and inequality measures as well as the cost of living index.

3.3.1 Poverty measures

There is a wide range of indicators measuring energy or fuel poverty[1] (see e.g. Lowans et al., 2021). Most common is the measurement with an energy to income ratio, which corresponds to households that spend more than a certain share of their income on energy (e.g. Berry, 2019; Boardman, 1991; Heindl and Schuessler, 2015; Okushima, 2016; Pachauri et al., 2004; Phimister and Roberts, 2015). Some use a more flexible form and define a threshold, which is set at twice the median ratio in order to account for changes in energy prices over time (e.g. CGDD, 2016; Heindl, 2015). The UK applies the definition of Hills' (2012) Low Income High Costs (LIHC) indicator, where households are considered fuel poor if a) *they had required fuel costs that were above the median level*; and b) *were they to spend that amount, they would be left with a residual income below the official poverty line* (Hills, 2012, p. 33). In some cases, the applied indicators include in addition to expenses also housing attributes such as building age or transport accessibility, i.e. factors determining high energy demand (e.g. Charlier and Legendre, 2018; Llera-Sastresa et al., 2017; Mattioli et al., 2019). In the light of carbon pricing of mobility and heating, transport poverty also enters the political and social debate. Until recently there was a lack in the debate on transport poverty. However, in light of ambitious climate policy and rising gasoline prices, this research area will become more important (Igawa and Managi, 2022). Several studies broaden their definition on energy or fuel poverty and include transport expenditure such as spending on motor fuels (CGDD, 2016; Legendre and Ricci, 2015; Mattioli et al., 2018; Mayer et al., 2014). For instance, Hills' (2012) LIHC indicator lends itself to the integration of transport costs, which can be easily added to the energy costs threshold. Then the energy costs comprise both housing and transport, and the threshold is fixed as the median of the sum of these two expenses (see Mattioli et al., 2018). We orient on these recent approaches and apply different measures of energy and fuel poverty, which are listed in Table 1 along with the respective share of households affected. Note that for labelling the indicators in Table 1 we usually use the term “energy” to refer to electricity and heating, and “fuel” or “transport” to refer to motor

[1] The terms of energy poverty and fuel poverty are often cross-used in the literature. When distinguished, energy poverty usually refers to a situation of lacking accessibility, fuel poverty to a situation of lacking affordability (see e.g. Li et al., 2014). In the present paper, it is all about affordability.

fuels. Across all indicators, the case study region Styria shows a share of energy and fuel poor households above the national average.

Table 1. Energy and fuel poverty definitions

Indicator	Definition	Reference and application	Case-Study share (Austrian share)
Energy poverty classic (EPC)	Households who spend more than 10% of their disposable income on energy (electricity and heating).	Boardman's (1991) TPR indicator, Berry (2019)	12.5% (8.1%)
Energy poverty median (EPM)	Energy expenditure (electricity and heating) in absolute amounts (EUR) is higher than twice the national median.	CGDD (2016)	14.9% (10.4%)
Fuel and energy poverty median (FPM)	Fuel and energy expenditure (electricity, heating, and motor fuel) in absolute amounts (EUR) is higher than twice the national median.	CGDD (2016)	12.4% (11.3%)
Energy poverty LIHC (EPL)	Energy expenditure (electricity and heating) in absolute amounts (EUR) is higher than the national median, and its residual income net of respective energy expenditure is below the poverty line.	Hills' (2012) LIHC indicator	13.3% (8.8%)
Fuel and energy poverty LIHC (FPL)	Fuel and energy expenditure (electricity, heating and motor fuel) in absolute amounts (EUR) is higher than the national median, and its residual income net of respective fuel and energy expenditure is below the poverty line	Hills' (2012) LIHC indicator, Mattioli (2016), Mattioli et al. (2018)	10.4% (7.1%)
Transport poverty LIHC (TPL)	Motor fuel expenditure in absolute amounts (EUR) is higher than the national median, and its residual income net of respective motor fuel expenditure is below the poverty line	Hills' (2012) LIHC indicator, Mattioli (2016), Mattioli et al. (2018)	8.4% (6.0%)

3.3.2 Cost of living index

Following Lewbel and Pendakur (2009), we use the cost of living metric (CoL) to measure changes in welfare, but in a slightly modified version that also incorporates potential transfers from compensation schemes:

$$CoL = \frac{C(\boldsymbol{p}_1, u_0, \boldsymbol{z}, \varepsilon) - t_1}{C(\boldsymbol{p}_0, u_0, \boldsymbol{z}, \varepsilon)} - 1 \tag{3}$$

where $x = C(\boldsymbol{p}, u, \boldsymbol{z}, \varepsilon)$ denotes the minimum total expenditure needed for an individual household with observable characteristics $\boldsymbol{z}$, unobserved preference characteristics ε and facing log price vector $\boldsymbol{p}$ to attain utility level u. Moreover, $\boldsymbol{p}_0$ and u_0 refer to the initial log price vector and utility level in the baseline, while $\boldsymbol{p}_1$ denotes the final log price vector including the carbon tax. The term t_1 refers to any compensating transfer accompanying the carbon tax. The cost of living index as defined in (3) thus provides the relative change in the cost of living to maintain the initial level of utility after price changes, while accounting for any potential compensating transfers accompanying these price changes.

If $t_1 = 0$, (3) reads as

$$CoL = \frac{C(\boldsymbol{p}_1, u_0, \boldsymbol{z}, \varepsilon)}{C(\boldsymbol{p}_0, u_0, \boldsymbol{z}, \varepsilon)} - 1 \tag{4}$$

which is just a first order Taylor expansion of the original formula used by Lewbel and Pendakur (2009):

$$ln\left(\frac{C(\boldsymbol{p}_1, u_0, \boldsymbol{z}, \varepsilon)}{C(\boldsymbol{p}_0, u_0, \boldsymbol{z}, \varepsilon)}\right) \tag{5}$$

3.3.3 Gini index

As in Eisner et al. (2021), we use the Gini index (Gini, 1912) to measure changes in equality. The Gini index measures statistical dispersion and is intended to indicate the income or wealth inequality across the population. The Lorenz curve, which plots the cumulative percentages of total income against the cumulative population, represents the basis for deriving the Gini index, which is defined as follows:

$$G = S/(S + T) \tag{6}$$

where S is the area between the hypothetical line of total equality, i.e. the ideal Lorenz curve, and the actual Lorenz curve, and T is the area between the actual Lorenz curve and the axes. A value of zero denotes total equality; a value of 1 total inequality.

3.3.4 Social Welfare

We follow Tovar Reaños and Wölfing (2018) and Creedy and Sleeman (2006) and estimate the aggregate change in social welfare by using the metric of “equivalent income”. “Equivalent income” is defined by King (1983) as the income level which gives the same utility as the current income level, but under a set of different prices. Adopting this definition to expenditure – in demand systems, consumption expenditure is a proxy for income – we define “equivalent expenditure” x_e as the solution to:

$$V(x_e, \boldsymbol{p}_0, \boldsymbol{z}, \varepsilon) = V(x_0 + t_1, \boldsymbol{p}_1, \boldsymbol{z}, \varepsilon) \tag{7}$$

where $u = V(x, \boldsymbol{p}, \boldsymbol{z}, \varepsilon)$ is the indirect utility for an optimal consumption vector of an individual household with total expenditure x, observable characteristics $\boldsymbol{z}$, unobserved preference characteristics ε and facing log price vector $\boldsymbol{p}$. Moreover, $\boldsymbol{p}_0$ and x_0 refer to the initial log price vector and the initial total expenditure in the baseline, while $\boldsymbol{p}_1$ denotes the final log price vector including the carbon tax. The term t_1 again refers to any compensating transfer accompanying the carbon tax. The mean equivalent expenditure (or income) is then defined as

$$MEE = \frac{1}{\sum_{h \in H} \omega_h} \sum_{h \in H} \frac{x_{e,h}}{hsize_h} * \omega_h \tag{8}$$

where $x_{e,h}$ is the equivalent expenditure of household h, $hsize_h$ denotes the size of household h measured in terms of the OECD-modified equivalence scale (Hagenaars et al., 1994), ω_h is the (statistical) weight of household h in the household survey from which the expenditure data is drawn (see chapter 4), and H denotes the set of considered households.

Based on the mean equivalent expenditure (or income), aggregated social welfare is defined as follows (Creedy and Sleeman, 2006; Tovar Reaños and Wölfing, 2018):

$$SW = (1 - G) \times MEE \tag{9}$$

4 Data

Household data on expenditure and income are drawn from the Austrian Household Budget Survey (HBS) provided by Statistics Austria. We used data from the HBS of the years 2004/2005, 2009/2010, 2014/2015 and 2019/2020. Household data is matched with consumer price indices at a state level for the years 2004, 2005, 2009, 2010, 2014, 2015, 2019 and 2020, published by Statistics Austria. The goods classification matches exactly those of HBS (both are classified in COICOP). Note, that the model is estimated for the entire Austrian data set and that all results and insights are illustrated for Styria, our case study region.

As in Eisner et al. (2021), the model comprises eight commodity groups: motor fuels, electricity, heating, housing, food, non-durables, durables and others. In comparison to other pertinent studies (e.g. Berry, 2019; Tovar Reaños, 2021; Tovar Reaños and Lynch, 2022), the distinction between the main energy consumption categories motor fuels, electricity and heating is of key importance. Eisner et al. (2021) already underscored that the impact channels and hence the vulnerability to price increases differ strongly between electricity and heating. Thus, in order to evaluate the effects of carbon pricing, a separate representation of energy goods is indispensable. Heating subsumes the subcategories natural gas, heating oil, biomass, coal, district heating and alternative heating (e.g. heat pumps). Housing comprises maintenance and repair, operating costs rent and rent equivalent for homeowners. Food includes food and beverages consumed at home, while hotels and restaurants are subcategories of non-durables. The latter encompasses public and private services such as communication, education and health. Durable goods represent long-term investments due to their high transaction costs and comprise among others, mobility (except fuels), household appliances, clothes and leisure. "Others" includes the remaining expenditure categories such as financial activities, personal hygiene and insurance as well as social security and other services. Table 10 in the appendix reports the respective average expenditure shares for Austria as a whole and the case study region Styria.

The specified EASI demand system allows taking household preferences and hence heterogeneous preferences into account; an aspect neglected in many studies (Berry, 2019; Pashardes et al., 2014; Renner et al., 2018). Similar to Eisner et al. (2021), we thus include socio-demographic variables, which allow differentiating the consumption behavior of different groups in society. In particular, we include a variety of socio-demographics and housing attributes influencing energy consumption such as the household composition, built year and primary energy source of the heating system. The selection of variables is based on pertinent studies analyzing energy and fuel poverty.

5 Estimation results

5.1 *Engel Curves*

Figure 1 illustrates non-parametric kernel regressions of budget shares over total household consumption (as mentioned, consumption is a proxy for income in demand systems), showing the distributional incidence for the three energy goods electricity, heating and motor fuels in the case study region Styria. These so called Engel curves give an initial indication of how households of different ability to pay will be affected by price changes. For heating and electricity we find the highest budget shares among low-income households, while for motor fuels lower middle class to middle class households show the highest shares. Furthermore, the budget shares for electricity and heating are decreasing with rising income, thus showing a regressive behavior.

The non-linear form of the Engel curves underscores that the EASI demand system is preferable compared to other formulations such as AIDS or its quadratic version QUAIDS, which are only able to consider linear or quadratic Engel curves. Additionally, the EASI parameters are statistically significant and greater than zero for the polynomials of up to degree five. This confirms the nonlinearity of the Engel curves and justifies the approach taken in this study.

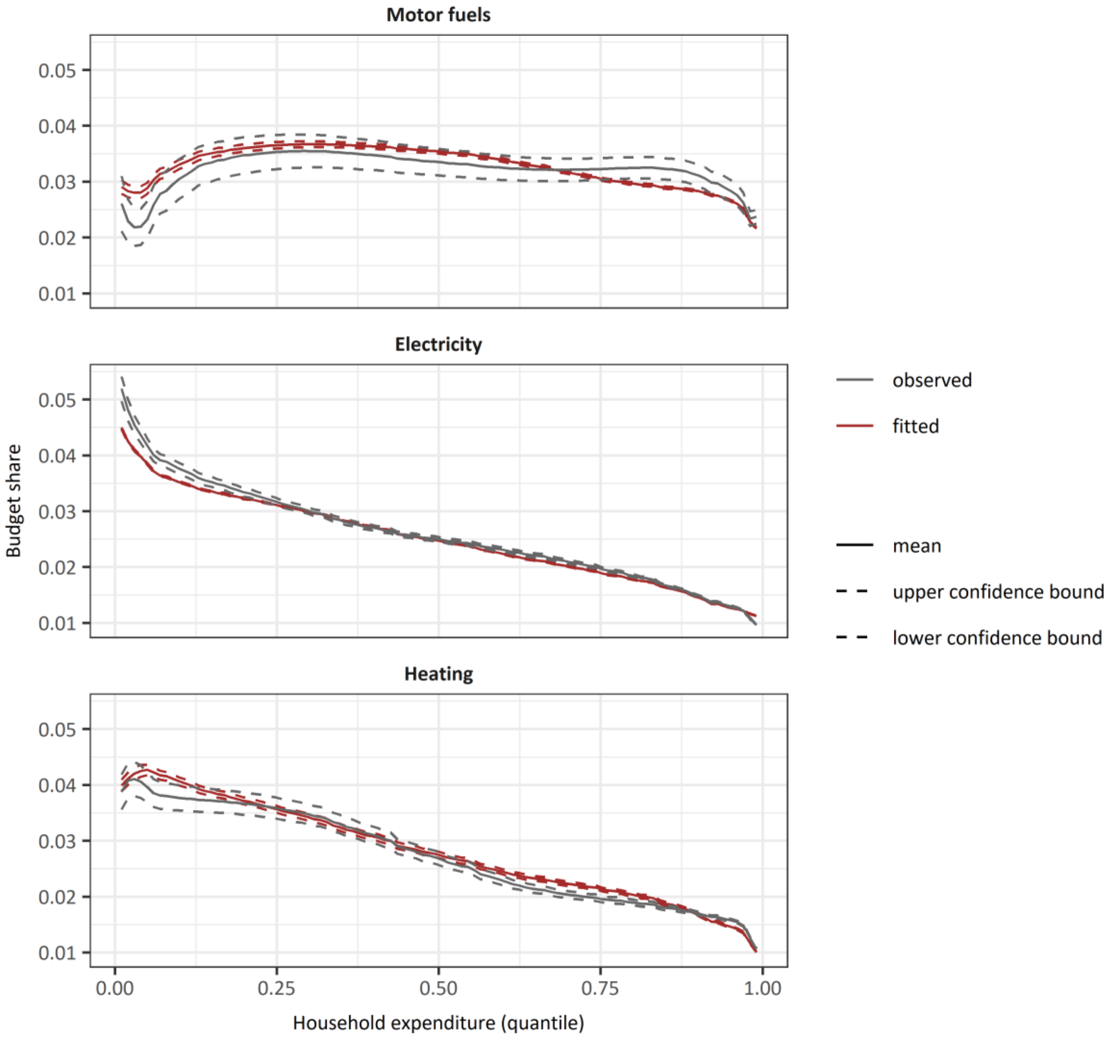

Figure 1. Non-parametric Engel curves for Styria: expenditure share of commodities over monthly household expenditure (in quantiles)

5.2 *Elasticities*

To basically allow comparisons with other studies, Table 3 and Table 4 show the commonly reported uncompensated price elasticities (see e.g. van der Ploeg et al. (2022) on how to calculate uncompensated price elasticities in EASI demand systems). Nevertheless, direct comparisons of our results with estimates from other studies are difficult and need to be taken with caution, since there are most often differences in the chosen methodological approach, country-specific characteristics, the commodity groupings used or the time horizon considered (see Table 2).

Table 2: Overview on some key facts of studies used for elasticity comparisons

Source	Country	Method	Time horizon	Energy goods considered
Tiezzi (2005)	Italy	AIDS	1985-1996	- Domestic fuels - Transport fuels
Nikodinoska and Schröder (2016)	Germany	DQUAIDS	1993-2008	- Electricity - Car fuels - Other fuels
Schulte and Heindl (2017)	Germany	QES	1993-2008	- Electricity - Heating - Transport (car fuels, public transport)
Renner et al. (2018)	Mexico	QUAIDS	2002-2014	- Electricity - Motor fuels - Gas
Tovar Reaños and Wölfing (2018)	Germany	EASI	2002-2012	- Electricity - Heating - Transport (private, public)
Liu et al. (2022)	China	QUAIDS	2005-2019	- Coal - Gasoline - Diesel - LPG - NG - Electricity
Tovar Reaños (2021), Tovar Reaños and Lynch (2022)	Ireland	EASI	1994/95-2015/16	- Energy (heating, lighting) - Transport (private, public)
van der Ploeg et al. (2022)	Germany	EASI	1993-2013	- Electricity - Heating - Transport

AIDS = Almost Ideal Demand System, QUAIDS = Quadratic Almost Ideal Demand System, DQUAIDS = Demographically-Scaled Quadratic Almost Ideal Demand System, QES = Quadratic Expenditure System, EASI = Exact Affine Stone Index

Table 3 shows the uncompensated own and cross price elasticities for the first quartiles of household expenditure (for comparison, Table 12 in the Appendix reports the respective elasticities for the fourth expenditure quartile). The first row in Table 3, for example, shows the change in the demand for each commodity in percentage if the price of food increases by 1%. Table 4 additionally reports the uncompensated own-price elasticity for the energy goods motor fuels, electricity and heating for different vulnerable groups, expenditure quartiles Q1 and Q4 as well as total households. It is important to note that the reported price elasticities represent medium to long-run rather than short-run elasticities. Hence, they also comprise changes in demand due to long-term effects, like changes in the social environment or lifestyle and the purchase or replacement of durable goods over time (e.g. energy efficient improvements) as alternative response to price changes (Schulte and Heindl, 2017).

For low-income households, motor fuels show by far the highest own-price elasticity, while the one for electricity is the smallest (Table 3). The own-price elasticity of electricity is close to zero and hence demand is quite inelastic. This is not surprising, since electricity is an essential good and households often show little reaction to price changes. Pellini (2021), for example, also observes an inelastic residential electricity demand, although for Austria as a whole. The same holds true for Schulte and Heindl (2017) and van der Ploeg et al. (2022) for Germany, who find the own-price elasticity of electricity to rank amongst the lowest of all good categories they consider and exceeded by the price responsiveness for heating. In contrast to our findings for Styria, the own-price elasticity of motor fuels – or of the broader category private and public transportation – is often found to be rather inelastic (see e.g. Nikodinoska and Schröder, 2016; Schulte and Heindl, 2017; Tovar Reaños, 2021; Tovar Reaños and Lynch, 2022; van der Ploeg et al., 2022). Exceptions include Tiezzi (2005), Renner et al. (2018) and Liu et al. (2022), who find somewhat elastic own-price elasticities of motor fuels for Italy, Mexico and China.

Taking a closer look, our results reveal differences for vulnerable and low-income households regarding the magnitude of the elasticities, compared to the Styrian average or high-income households. Table 4 underscores that energy or fuel poor households and low-income households (households in EPL, FPL, TPL, EPC, and Q1) have smaller own price elasticities than more affluent ones (Q4) in case of heating. Due to this limited price response compared to more affluent households, vulnerable households face higher burdens in case of price increases for heating. For electricity and motor fuels, by contrast, own-price elasticities of energy poor and low-income households are somewhat (electricity) or partly even much larger (motor fuels). In particular, the decrease in the demand of motor fuels following a price increase is often nearly twice as high for vulnerable and poor households than for the more affluent ones. An exception are those household groupings, whose poverty definition includes expenditure on motor fuels (e.g. FPL, TPL). They either show only slightly higher or even lower own-price elasticities for motor fuels than more affluent households, which might be an indication of lacking alternatives to car use. Corresponding results in the literature are quite diverse: Nikodinoska and Schröder (2016), Tovar Reaños and Wölfing (2018) and van der Ploeg et al. (2022) also find the own-price elasticity of electricity to be higher for low-income households (Q1) than high-income households (Q4) in Germany, while Schulte and Heindl (2017) come to the opposite result for Germany. In contrast to our Styrian estimates, Nikodinoska and Schröder (2016) and Tovar Reaños and Lynch (2022) find German and Irish low-income households to respond less elastic to price changes in motor fuels or transportation than high-income households. Results of van der Ploeg et al. (2022) for Germany, however, show low-income households to be slightly more elastic. For heating, we again find both directions in the literature (see e.g. Schulte and Heindl, 2017; Tovar Reaños and Lynch, 2022; Tovar Reaños and Wölfing, 2018; van der Ploeg et al., 2022).

Note also that applying the definition of the threshold of twice the median (EPM and FPM) without considering household income is likely to miss the target of energy and fuel poverty. For a considerable share of households in EPM and FPM the high energy and fuel expenditure traces back to a rather luxury, fuel-intensive lifestyle. When adding low-income to the definition, by following Hills (2012), these affluent households are excluded and the intended target of vulnerability is better depicted.

Table 3. Uncompensated own and cross price elasticity for Styria, evaluated at mean value budget shares of households in expenditure quartile 1

Δ% q	*Food*	*Motor fuel*	*Electricity*	*Heating*	*Housing*	*Non durables*	*Durables*	*Other*
Δ% p								
Food	**-1.858**	4.436	-0.749	-0.019	0.259	-0.344	-0.354	1.229
	(0.617)	(1.893)	(0.68)	(0.325)	(0.028)	(0.394)	(0.224)	(1.772)
Motor fuel	0.628	**-3.564**	1.085	0.229	0.082	-0.042	0.196	-2.003
	(0.264)	(1.286)	(0.395)	(0.146)	(0.012)	(0.165)	(0.119)	(0.75)
Electricity	-0.143	1.328	**-0.254**	0.152	0.036	-0.324	-0.348	0.427
	(0.118)	(0.492)	(0.216)	(0.078)	(0.007)	(0.100)	(0.052)	(0.349)
Heating	-0.014	0.275	0.162	**-1.006**	0.031	-0.097	0.089	-0.320
	(0.060)	(0.192)	(0.082)	(0.122)	(0.009)	(0.100)	(0.043)	(0.181)
Housing	0.268	0.592	0.293	0.224	**-0.990**	-0.059	-0.509	-0.110
	(0.036)	(0.110)	(0.051)	(0.066)	(0.028)	(0.095)	(0.061)	(0.110)
Non durables	-0.036	-0.053	-0.651	-0.089	0.113	**0.651**	-0.897	0.038
	(0.167)	(0.500)	(0.243)	(0.230)	(0.031)	(0.403)	(0.139)	(0.486)
Durables	-0.049	1.286	-1.259	0.643	-0.039	-1.588	**-0.343**	0.515
	(0.172)	(0.652)	(0.23)	(0.179)	(0.036)	(0.252)	(0.174)	(0.473)
Other	0.502	-5.289	0.984	-0.568	0.039	-0.011	0.181	**-1.045**
	(0.654)	(1.986)	(0.742)	(0.363)	(0.031)	(0.424)	(0.228)	(2.003)

Bootstrap standard errors in brackets. Elasticities are evaluated at the mean budget shares for households at the first total expenditure quartile. Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Table 4. Uncompensated own price elasticity in Styria, evaluated at mean value budget shares of households for different groupings

	Own price elasticity of:		
	Motor fuel	*Electricity*	*Heating*
Energy poverty classic (EPC)	-3.366	-0.407	-1.108
	(1.374)	(0.181)	(0.075)
Energy poverty median (EPM)	-2.085	-0.487	-1.270
	(1.216)	(0.191)	(0.068)
Energy poverty LIHC (EPL)	-3.616	-0.327	-1.063
	(1.362)	(0.186)	(0.089)
Fuel and energy poverty median (FPM)	-0.894	-0.430	-1.290
	(0.531)	(0.241)	(0.087)
Fuel and energy poverty LIHC (FPL)	-1.516	-0.375	-1.175
	(0.602)	(0.171)	(0.082)
Transport poverty LIHC (TPL)	-1.009	-0.270	-1.208
	(0.481)	(0.185)	(0.107)
Expenditure quartile 1 (Q1)	-3.564	-0.254	-1.006
	(1.286)	(0.216)	(0.122)
Expenditure quartile 4 (Q4)	-1.399	0.182	-1.476
	(1.314)	(0.409)	(0.178)
Total Styrian population	-2.180	-0.160	-1.132
	(0.855)	(0.203)	(0.104)

Bootstrap standard errors in brackets. Elasticities are evaluated at the mean budget shares for households in the respective group. Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Turning to expenditure elasticities (see Table 5), we find that most goods are necessities with an expenditure elasticity lower than one. For low-income households, the expenditure elasticity of motor fuels is however fairly close to one, indicating that the demand for motor fuels increases quickly with rising income in this household class. The estimated elasticities are very similar across expenditure quartiles in terms of the order of goods, but low-income households usually show higher values in absolute terms. Nikodinoska and Schröder (2016), Tovar Reaños and Wölfing (2018) and van der Ploeg et al. (2022) also find higher expenditure elasticities for low-income households (Q1) compared to high-income households (Q4). However, their expenditure elasticity estimations for Germany are usually somewhat higher than our results for Styria. Tovar Reaños and Lynch (2022), by contrast, report expenditure elasticities of Irish households for energy (subsuming electricity and heating) and transport (comprising private and public transport) that are slightly increasing with total expenditure. Similarly, Schulte and Heindl (2017) find expenditure elasticities for electricity, heating and transport (motor fuels and public transport) in Germany to increase with total expenditure. Their estimates on the mean expenditure elasticities for electricity, heating and transport are, however, in the same order of magnitude as our results for Styria.

Table 5. Expenditure elasticity for the first and last expenditure quartile and the mean

Δ% q	*Food*	*Motor fuels*	*Electricity*	*Heating*	*Housing*	*Non durables*	*Durables*	*Other*
Q1	0.701	0.988	0.391	0.435	0.469	1.813	1.986	1.269
	(0.008)	(0.024)	(0.015)	(0.017)	(0.019)	(0.044)	(0.029)	(0.033)
Mean	0.592	0.792	0.285	0.306	0.396	1.357	1.701	1.010
	(0.008)	(0.016)	(0.013)	(0.015)	(0.014)	(0.018)	(0.009)	(0.015)
Q4	0.396	0.594	0.126	0.081	0.472	0.979	1.468	0.955
	(0.020)	(0.029)	(0.045)	(0.044)	(0.039)	(0.031)	(0.010)	(0.020)

Bootstrap standard errors in brackets. Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

In addition to the presented elasticities, Table 11 in the Appendix reports the significant parameter estimates of the three energy goods motor fuels, heating and electricity.

5.3 *Emissions*

For Austria, the sum of CO_2 emissions resulting directly and indirectly in the household sector equals 52 $MtCO_2$[2] in 2019, with 15 $MtCO_2$ accounting for direct emissions and 37 $MtCO_2$ accounting for indirect emissions. Direct emissions of the household sector match emissions of the national inventory (Anderl et al., 2018). To the authors knowledge, there are no current estimations on the carbon footprint of Austria; only Steininger et al. (2018) and Smetschka et al. (2019) who report around 80 $MtCO_2e$ for the year 2008. Emissions for Styria, the case study region, sum up to 7.3 $MtCO_2$ (14% of total Austrian emissions), with 2.1 $MtCO_2$ accounting for direct emissions and 5.2 $MtCO_2$ accounting for indirect emissions.

[2] The consumption-based approach adopted only accounts for territorial emissions in domestic production.

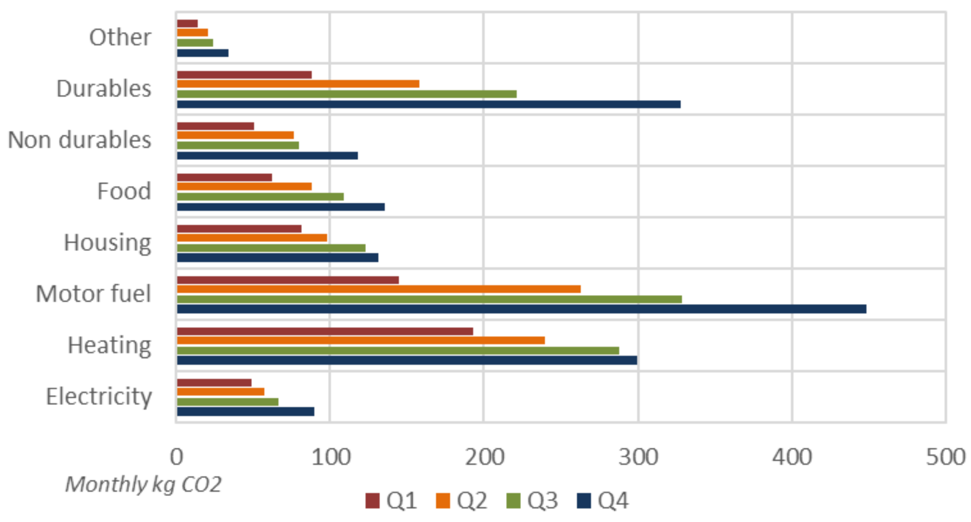

Figure 2. Average monthly emission consumption across household distribution in Styria.

Figure 2 illustrates a Styrian household's average carbon footprint associated with its consumption by total expenditure quartile. In line with van der Ploeg et al. (2022), Theine et al. (2022) and Renner et al. (2018), carbon footprints rise with expenditure quartiles. Motor fuels have the highest carbon footprint, followed closely by durables and heating. Electricity shows a relatively low carbon footprint, since Austria's electricity mix is to a large part renewable and hence carbon neutral. Furthermore, in comparison to the Austrian average, an average Styrian household shows much higher emissions for energy consumption, in particular heating and motor fuels. These differences trace back to longer car travel distances in Styria, due to its rural nature as well as poor public transport connections, and a disproportionately high share of oil heating systems.

6 Simulation and scenarios

We simulate a carbon tax scenario where prices of all energy goods in non-ETS[3] increase according to their carbon content. The modelling of this scenario aligns itself to the recent literature (Berry, 2019; Tovar Reaños and Wölfing, 2018; van der Ploeg et al., 2022) and affects all carbon based energy sources (gas, oil, coal, motor fuel). The carbon tax rate is modelled on top of current, i.e. 2019, energy prices and is based on the proposition of the Austrian

[3] Be aware that the carbon price for electricity is already governed by the emission trading system (ETS) of the European Union.

government, which – linearly extrapolated – results in a price of EUR 90/tCO_2 in 2030. Assuming a pre-crisis inflation rate, which seems consistent since the proposition dates back before the energy crisis and might be adapted accordingly, this corresponds to about EUR 77/tCO_2 in prices 2019. In order to test for sensitivity, we also simulate a carbon price of EUR 156/tCO_2 in 2030, i.e. EUR 134/tCO_2 in prices 2019, which, according to the Impact Assessment of the European Commission (e.g. European Commission, 2021a, 2021b, 2021c), aligns with the ambitious climate targets of the EU 'Fit for 55' package (-48% carbon emissions by 2030).

6.1 *Carbon tax scenario*

Analyzing the cost-of-living impacts for different socio-economic and socio-demographic characteristics reveals the following trends: First, rural households are more affected by carbon pricing than urban ones for all expenditure deciles (Figure 3)[4]. As reported in the last row of Table 6, the impact is more than twice as high for most rural households. Second, middle-income groups are hit the strongest, while the most affluent and the extreme poor are least affected. However, differences across expenditure deciles are modest and the magnitude of the effects depends on other characteristics such as household composition or region. Taking a closer look reveals that the carbon tax induced changes in motor-fuels are the dominant impact channel. While a carbon tax in heating shows a slight regressive nature, motor-fuels show a clear inverse u-shape, where middle-income groups are substantially higher affected. Direction and pattern of distributional impacts of a carbon tax of EUR 134/tCO_2 mirror these results, but on a higher magnitude (see Figure 5 and Table 13 in the Appendix).

[4] Note that the sample of urban households is comparably small on decile level, which makes the results more volatile than for rural households or all Styrian households.

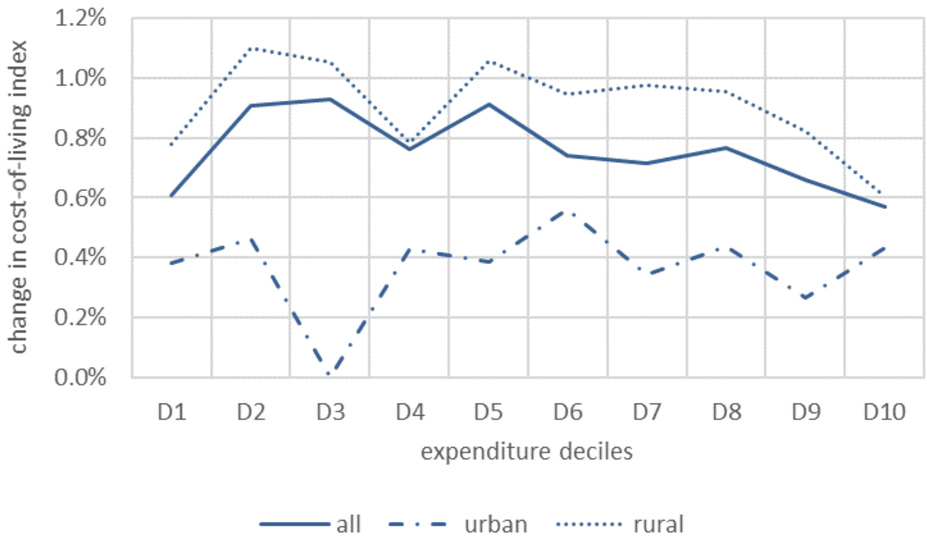

Figure 3. Effects (change in cost-of-living index in %) of a carbon tax of EUR 77/tCO_2 across equalized expenditure deciles and region type. The underlying household data distinguish three types of urbanization (urban, suburban, rural), of which the two extremes are plotted here.

Thus, turning to energy and fuel poor households shows that those are hit the strongest among all household specifications (see Table 6). In most cases the impact is nearly twice as high as the average one on Q1. Again, the effect is much stronger for households in rural than in urban areas. Turning to the different definitions of energy and fuel poverty underscores that not accounting for motor fuel expenditure strongly underestimates the extent of distributional impacts. This is not surprising given the fact that price changes in motor fuel are the dominant impact channel.

Table 6. Cost-of-living effects (%-change) of a EUR 77/tCO_2 carbon tax on different household groups and socio-demographics

	%-change in cost of living		
	Total	*Rural*	*Urban*
Energy poverty classic (EPC)	1.073%	1.362%	0.576%
Energy poverty median (EPM)	1.435%	1.523%	1.248%
Energy poverty LIHC (EPL)	1.070%	1.248%	0.546%
Fuel and energy poverty median (FPM)	1.566%	1.678%	1.009%
Fuel and energy poverty LIHC (FPL)	1.548%	1.629%	1.247%
Transport poverty LIHC (TPL)	1.513%	1.701%	1.265%
Expenditure quartile 1 (Q1)	0.817%	0.963%	0.369%
Expenditure quartile 4 (Q4)	0.664%	0.801%	0.338%
Total Styrian population	0.769%	0.923%	0.383%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

6.2 *Revenue recycling measures*

We simulate five compensation schemes, where the carbon tax revenues are recycled, and analyze their potential to mitigate negative distributional impacts. In total, the carbon tax of EUR 77/t generates revenues of EUR 0.98 billion in Austria, where around EUR 0.14 billion are attributable to the case study region Styria. In all compensation schemes, the total revenues are reimbursed. Table 7 gives details on the applied compensation schemes. Note that the respective amount of compensation shown in Table 7 refers to a single-person household (often called the normalized transfer). Depending on the compensation scheme, either the same amount of normalized transfer is disbursed to each household ("flat") or distinct amounts are transferred, depending on the household's income ("income-based"), vulnerability ("target-group-based") or region ("density-based" and "region-based"). The mechanisms of the density-based and the region-based scheme are quite similar. They mainly differ in the number of regions distinguished, were the latter follows the regional differentiation of the government's proposition (*Klimabonusgesetz*, 2022).

In line with the OECD modified household equivalence scale (Hagenaars et al., 1994), households receive an additional 50% of the normalized amount for every subsequent person aged 14 and over, and 30% for each child aged under 14 living in the household. For the region-based scheme, an additional household-size-related distribution rule is simulated that coincides with the rule actually used by the Austrian government, i.e. persons aged 18 and over receive 100% of the normalized amount and persons aged below 18 receive 50%. Compared to the distribution rule based on the OECD modified equivalence scale, larger households tend to be better off with the rule of the Austrian government.

Table 7. Overview of applied compensation schemes

Compensation scheme	***Description***
Flat (FLC)	Every household receives the same amount of cash transfer (193 Euro p.a. for a single household).
Income-based (INC)	Households in the first and second income quartile receive double the payment (i.e. 260 Euro p.a. for a single household) than households in income quartile three and four (i.e. 130 Euro p.a. for a single household).
Target-group-based (TGC)	Households defined as energy or fuel poor receive double the payment (346 Euro p.a. for a single household) than households not defined as energy or fuel poor (173 Euro p.a. for a single household).
Density-based (DEC)	Households living in non-urban areas (suburban and rural) get by the factor of 1.5 a higher payment (i.e. 216 Euro p.a. for a single household) than households living in urban areas (i.e. 144 Euro p.a. for a single household).
Region-based (REC) (regional differentiation based on government proposition)	The cash payment depends on the region households live in: Vienna (129 Euro p.a. for a single household), other urban areas (171 Euro p.a. for a single household), suburban centers (214 Euro p.a. for a single household) and rural regions (258 Euro p.a. for a single household).
Region-based (REC_{GOV}) (regional differentiation and household-size-related distribution rule based on government proposition)	The cash payment depends on the region households live in: Vienna (98 Euro p.a. for a full-aged single household), other urban areas (131 Euro p.a. for a full-aged single household), suburban centers (163 Euro p.a. for a full-aged single household) and rural regions (197 Euro p.a. for a full-aged single household). The household-size-related distribution scheme follows the government proposition.

Figure 4 illustrates the welfare effects of the applied transfer schemes and, for comparison, the no-transfer carbon tax scenario (NTC) as reference point. We find that all transfer schemes are able to compensate for the regressive effects of the carbon tax scenario. Shape and direction of effects are similar in all schemes: in the first and second quartile the cost-of-living decreases, i.e. welfare increases, with extremely poor households benefitting the most. In the third and fourth quartile effects are still welfare-reducing, but to a lesser extent. Hence, in combination with the considered compensation schemes, the carbon tax shows a progressive nature with low-income households being the least and high-income households the most affected. In total, the strongest positive effects on cost-of-living are generated in the target-group-based scheme, followed by the income-based scheme.

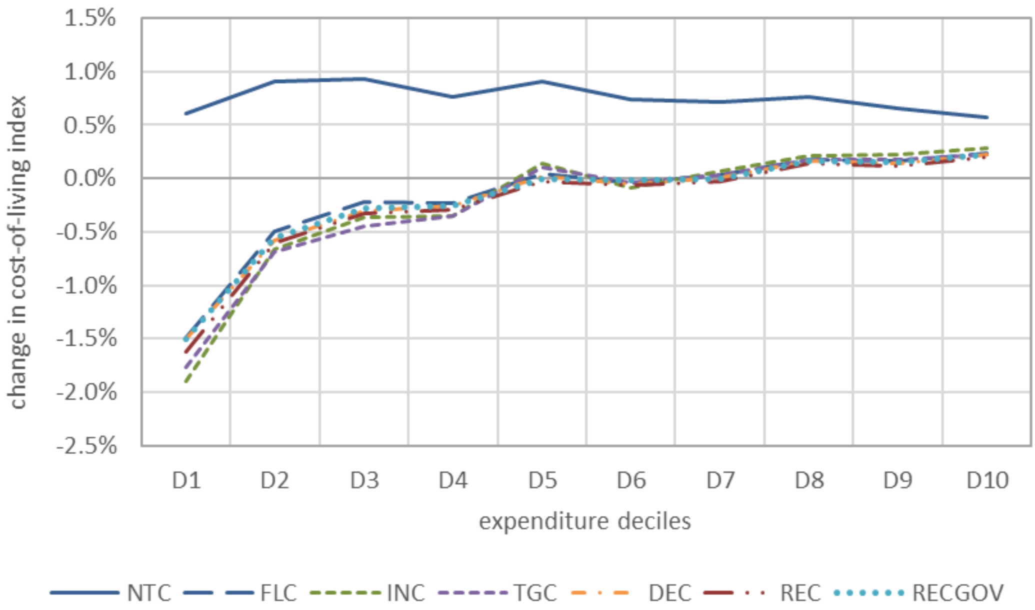

Figure 4. Effect [change of cost-of-living in %] of different transfer schemes across expenditure deciles, assuming a carbon tax of EUR 77/tCO_2

Table 8 shows the cost-of-living effects for the vulnerable groups and reveals differences regarding impact channel and magnitude of effects: First, the target-group-based scheme (TGC) works as intended and results in the strongest improvements for the defined poor and vulnerable groups. The opposite is found for the flat transfer (FLC) and for the second version of the region-based transfer, which applies a household-size-related distribution rule deviating from the other transfer schemes (REC_{GOV}). They both show the smallest improvements in cost-of-living for the vulnerable households compared to the no-transfer scenario (NTC).

Second, the income-based scheme highlights that poverty measures, which base their definition on both, income and energy expenditure, are able to detect the most vulnerable ones. The income-based scheme, which allocates the double payment to low-income households, yields a much higher increase – or lower decrease – in welfare in the groups following Hills' (2012) low-income high cost definition (EPL, FPL, TPL) compared to the groups based solely on high cost definitions (EPM, FPM). Note also, that for household groups based on definitions without income consideration (EPM, FMP), the cost of living increases independent of the compensation scheme. Based on the learnings from Figure 4, this is a further indication that these groups include a high share of rather affluent households and thus do not capture energy and fuel poverty as intended.

Third, on an overall Styrian level the density-based compensation scheme more or less mirrors the effects on vulnerable groups of the income-based scheme. Although the pattern among the vulnerable groups is similar for urban and rural areas, taking a closer look shows that, as intended, the compensating effects (i.e. the difference between NTC and DEC) are much stronger in rural areas (see Table 15 and Table 16 in the Appendix). As in case of the no-transfer carbon tax scenario, the negative welfare impacts are still higher in rural areas for most household groupings, but the difference is smaller. Similar conclusions can be drawn for the region-based schemes.

Table 8. Effects (%-change in cost-of-living) of different transfer schemes across energy and fuel poor groups, assuming a carbon tax of EUR 77/tCO_2

Household groups	*NTC*	*FLC*	*INC*	*TGC*	*DEC*	*REC*	*REC_{GOV}*
EPC	1.073%	0.019%	-0.335%	-0.743%	-0.029%	-0.070%	0.096%
EPM	1.435%	0.726%	0.684%	0.481%	0.662%	0.639%	0.723%
EPL	1.070%	-0.063%	-0.494%	-0.955%	-0.133%	-0.128%	0.047%
FPM	1.566%	0.962%	0.976%	0.826%	0.907%	0.871%	0.941%
FPL	1.548%	0.536%	0.191%	-0.218%	0.471%	0.463%	0.567%
TPL	1.513%	0.383%	-0.029%	-0.360%	0.352%	0.328%	0.445%
Expenditure quartile 1	0.817%	-0.793%	-1.045%	-1.041%	-0.857%	-0.914%	-0.842%
Total Styrian population	0.769%	-0.221%	-0.298%	-0.314%	-0.257%	-0.296%	-0.248%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

On an aggregate level, the evaluation focuses on annual CO_2 emissions (direct and total), social welfare in monthly EUR per household, overall change in cost-of-living and the Gini index to gauge inequality (see Table 9). The carbon tax of 77 EUR curbs direct emissions in Styria by 19.9% (total consumption based emissions by 6%) compared to the pre-tax level (Baseline). Due to the additional income of the different transfer schemes, emission reduction is reduced to about 19.5% for direct emissions and 5.4% for total emissions compared to the pre-tax level. The different compensation schemes hardly show any differences in terms of their dampening effect on tax-related emission reductions.

Turning to social welfare and equality highlights the regressive nature of the carbon tax. Without any compensation, the Gini index rises and social welfare is reduced by 0.8%. All transfer schemes are able to reduce inequality, even relative to the pre-tax level (Baseline). The results suggest that combining carbon taxation with a suitable compensation mechanism not only cushions the regressive nature of the tax but also has the ability to be net progressive. The targeted and income-based compensating mechanism are more effectively reducing negative welfare effects for the most vulnerable ones and hence reduce horizontal inequality.

Table 9. Aggregated results for a carbon tax of EUR 77/tCO$_2$ with different compensation schemes

	Social Welfare (monthly EUR per household)		*Gini index*	*%-change in cost-of-living*	*Direct Emissions (Mt CO$_2$ monthly)*		*Total emissions (Mt CO$_2$ monthly)*	
Baseline	1,506		0.2833	-	0.1819		0.6085	
NTC	1,494	-0.8%	0.2838	0.769%	0.1457	-19.9%	0.5718	-6.0%
FLC	1,510	0.3%	0.2816	-0.221%	0.1465	-19.5%	0.5754	-5.4%
INC	1,511	0.4%	0.2811	-0.298%	0.1465	-19.5%	0.5756	-5.4%
TGC	1,511	0.4%	0.2812	-0.314%	0.1466	-19.4%	0.5756	-5.4%
DEC	1,510	0.3%	0.2815	-0.257%	0.1465	-19.4%	0.5755	-5.4%
REC	1,511	0.4%	0.2815	-0.296%	0.1465	-19.4%	0.5757	-5.4%
REC_{GOV}	1,510	0.3%	0.2816	-0.248%	0.1465	-19.4%	0.5757	-5.4%

7 Discussion and conclusion

In this paper, we have analyzed the short-run impacts of a national carbon tax for heating and motor fuels and of five accompanying revenue recycling schemes on different types of households and regions in the Austrian Province of Styria, using the EASI demand system (Lewbel and Pendakur, 2009). The effects of carbon taxation and compensation schemes have been assessed in terms of welfare (cost of living index, social welfare), equality (Gini index) and emissions. Besides regional differences, a focus has been on the welfare impacts for particularly vulnerable households, for whose identification different measures of energy and fuel poverty from the literature have been applied.

We find that households in rural areas in Styria are clearly more affected by carbon pricing than households in urban areas, as measured by changes in the cost of living index. Reasons include a higher dependence on the car and a higher share of fossil-based heating systems. Compared to the Styrian average, urban-rural differences are usually less pronounced within the considered groups of energy and fuel poor households, as the respective group definitions capture some of the factors causing carbon tax impacts for rural and urban households to differ. For households classified as energy or fuel poor under the definitions considered, carbon tax impacts are up to two times higher than for the average Styrian household, and up to 2.2 times higher if they additionally live in rural areas.

Moreover, our results suggest to extend the vulnerability debate to all types of energy, including motor fuels. Not accounting for motor fuel expenditures in the vulnerability definition may substantially underestimate the effects of a carbon tax on vulnerable households – and thus distributional impacts – since price changes in motor fuels turn out to be the dominant impact channel of the considered tax. It is also important to note that the two times median expenditure definitions (EPM, FMP) are likely to miss the target of precisely identifying vulnerable households that are both, strongly affected by energy price increases and limited in their ability to shift their consumption to less carbon-intensive products. A considerable share of households in EPM and FPM shows a rather luxury, fuel-intensive lifestyle and basically has the financial means to replace energy intensive durables with more efficient ones. Following Hills (2012) and adding the low-income criterion to the vulnerability definition, by contrast, helps to exclude these affluent households and to better depict the intended target of identifying vulnerable households in the defined sense.

In line with the literature, we find that the combination of carbon taxation and an appropriate compensation scheme has the ability to turn the regressive nature of the tax into net progressivity. Compensation schemes that differentiate between vulnerable and non-vulnerable households (target-based) or between low and high-income households (income-based) are more effectively reducing negative welfare effects from the carbon tax for the most vulnerable ones and pre-tax income inequality than the other considered schemes. Thus, revenue recycling can be used to address equity issues, as for example also found by Tovar Reaños and Lynch (2022). However, there might be a non-negligible trade-off between administration costs and the degree of targeting.

Our results suggest a considerable potential for emission reductions due to carbon pricing, with direct consumption emissions decreasing by almost 20% (low tax scenario) and almost 30% (high tax scenario), and direct plus indirect consumption emissions decreasing by 6% (low tax scenario) and 9% (high tax scenario). With the considered compensation schemes, emission reductions are almost as high as without compensation, and there is a double dividend compared to the pre-tax scenario: in addition to emission reductions, social welfare and equality rise.

Transferring all revenues directly back to the households leads to overcompensation in the lower income deciles in all considered compensation schemes. Alternatively, parts of the revenues might be used for measures that improve households' ability to switch to a less carbon intensive consumption behavior, such as further development of public transport or further subsidies for substituting fossil-based heating systems and increasing buildings' energy efficiency. Such measures would help to foster the exit from the path dependency of vulnerability.

Note that a partial equilibrium framework, as adopted in this paper, ignores possible general equilibrium effects. Applying a recursive-dynamic computable general equilibrium model, Mayer et al. (2021) for instance find carbon pricing in Austria without any specific compensation of households to already be progressive. Future work could couple the general equilibrium framework with the detailed household-sector analysis of demand systems, aiming at further insights on distributional impacts in the more long-run perspective.

It might also be of great interest to repeat the present study as soon as the new wave of the Household Budget Survey is available. Data used in the present paper refer to the time before the COVID pandemic, the energy crisis and the high inflation. Hence, the tremendous price changes and their effects on consumption behavior have not yet been taken into account.

8 Appendix

Table 10. Summary statistics of expenditure shares (Austria / Styria)

	Mean	W.Means	Std. dev.
Goods:			
Motor fuels	3.5% / 3.9%	3.4% / 3.6%	0.04 / 0.04
Electricity	2.5% / 2.8%	2.5% / 2.8%	0.02 / 0.02
Heating	2.9% / 3.3%	2.9% / 3.3%	0.03 / 0.03
Housing	22.0% / 21.9%	22.6% / 22.6%	0.11 / 0.11
Food	16.6% / 16.9%	16.6% / 17.1%	0.09 / 0.09
Other non-durables	13.1% / 11.9%	13.5% / 12.2%	0.10 / 0.09
Durables	30.2% / 29.9%	29.3% / 28.8%	0.16 / 0.17
Other costs	9.1% / 9.5%	9.1% / 9.5%	0.07 / 0.08

Table 11. Regression results of the EASI demand system for motor fuels, electricity and heating

Regressors	**Budget share of …**		
	Motor fuels	**Electricity**	**Heating**
Constant		0.0591	
Couple without child		0.0115	
Single with child	-0.0253	0.0188	
Couple with child	-0.0142	0.0192	
Electricity		0.0198	
Gas			0.0693
Heating oil			0.0979
Wood			0.0317
Coal			0.0800
District heating			0.0724
Built after 2000		-0.0109	
Ownership flat	-0.0131		
Ownership house		0.0149	0.0235
Age 55+	-0.0263		0.0099
Ownership car	0.0936		
Urban	-0.0152		-0.0116
Living space	-0.0002	0.0002	0.0004
y × Couple without child		-0.0023	
y × Single with child	0.0069	-0.0043	
y × Couple with child	0.0041	-0.0041	
y × Electricity		-0.0051	
y × Gas			-0.0133
y × Heating oil			-0.0194
y × Wood			-0.0053
y × Coal			-0.0166
y × District heating			-0.0139
y × Built after 2000		0.0022	
y × Ownership flat			
y × Ownership house		-0.0030	-0.0057
y × Age 55+	0.0058		-0.0027
y × Ownership car	-0.0188	0.0017	
y × Urban	0.0023		0.0019
y × Living space	0.0000	0.0000	-0.0001
Price Heating			0.0277
Price Food	0.2968		
Price Durables	0.1170	-0.0736	0.0874
Couple without child × Price Living			0.0080
Couple with child × Price Living		0.0072	0.0191
Couple with child × Price Food	0.2814		
Couple with child × Price Durables			-0.0323
Ownership house × Price Motor fuels			0.0293
Ownership house × Price Heating	0.0293		-0.0380

Ownership house × Price Food			0.0709
Ownership house × Price Non Durables	0.0768		-0.0349
Ownership house × Price Durables			-0.0657
Age 55+ × Price Heating			-0.0196
Age 55+ × Price Living	0.0087		
Car ownership × Price Motor fuels	0.2795		
Car ownership × Price Living			0.0091
Car ownership × Price Food	-0.3881		
Car ownership × Price Durables	-0.1465	0.0506	
Urban × Price Electricity			-0.0134
Urban × Price Heating		-0.0134	
Urban × Price Living		-0.0092	
Urban × Price Non Durables			-0.0419

Note: due to the large amount of parameters in the EASI model, we only present the results of the energy goods with a significance level of 1%. The full set of parameters and standard errors are available from the authors upon request.

Table 12 Uncompensated own and cross price elasticity, evaluated at mean value budget shares of households in expenditure quartile 4

Δ% q	*Food*	*Motor fuel*	*Electricity*	*Heating*	*Housing*	*Non durables*	*Durables*	*Other*
Δ% p								
Food	**-1.689**	0.273	-0.569	0.280	0273	-0.014	-0.025	0.409
	(0.939)	(1.679)	(1.336)	(0.481)	(0.046)	(0.279)	(0.083)	(0.980)
Motor fuel	0.090	**-1.399**	2.518	0.524	0.152	0.221	-0.045	-0.799
	(0.515)	(1.314)	(0.910)	(0.287)	(0.022)	(0.148)	(0.048)	(0.546)
Electricity	-0.087	1.175	**0.182**	0.424	0.028	-0.250	-0.099	0.127
	(0.193)	(0.428)	(0.409)	(0.114)	(0.012)	(0.078)	(0.019)	(0.216)
Heating	0.043	0.299	0.534	**-1.476**	0.042	-0.064	0.007	-0.152
	(0.088)	(0.170)	(0.144)	(0.178)	(0.014)	(0.061)	(0.016)	(0.106)
Housing	0.383	0.669	0.309	0.371	**-1.200**	0.010	-0.124	0.057
	(0.063)	(0.102)	(0.116)	(0.105)	(0.035)	(0.057)	(0.026)	(0.075)
Non durables	0.063	0.884	-1.896	-0.289	0.078	**0.319**	-0.364	-0.258
	(0.324)	(0.560)	(0.632)	(0.388)	(0.047)	(0.261)	(0.057)	(0.359)
Durables	0.375	-0.176	-2.088	0.741	0.061	-0.0997	**-0.833**	0.297
	(0.322)	(0.603)	(0.523)	(0.343)	(0.074)	(0.193)	(0.092)	(0.337)
Other	0.425	-2.319	0.883	-0.655	0.094	-0.204	0.014	**-0.636**
	(0.883)	(1.602)	(1.351)	(0.526)	(0.049)	(0.278)	(0.078)	(1.070)

Bootstrap standard errors in brackets. Elasticities are evaluated at the mean budget shares for households at the fourth total expenditure quartile. Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

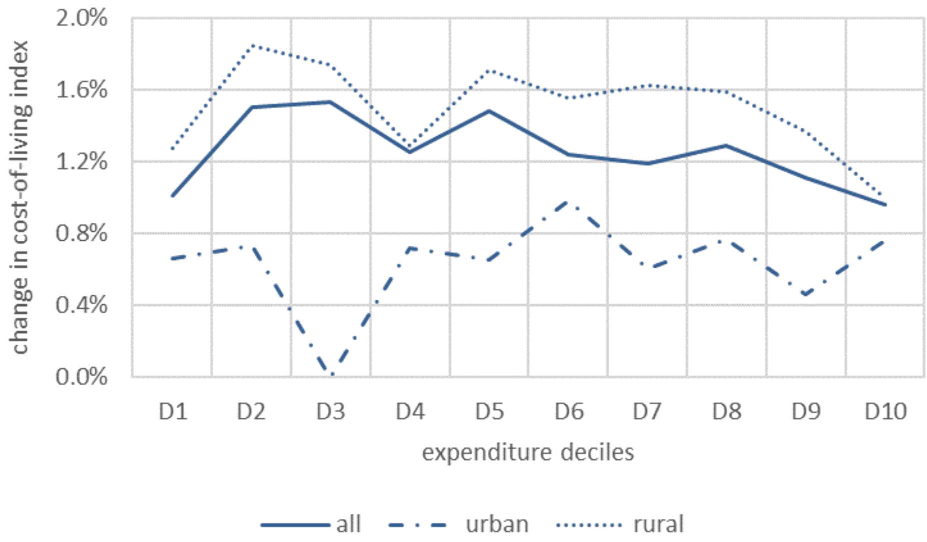

Figure 5. Effects (change in cost-of-living index in %) of a carbon tax of EUR 134/tCO_2 across equalized expenditure deciles and region type. The underlying household data distinguish three types of urbanization (urban, suburban, rural), of which the two extremes are plotted here.

Table 13. Cost-of-living effects (%-change) of a EUR 134/tCO_2 carbon tax on different household groups and socio-demographics

	%-change in cost of living		
	Total	*Rural*	*Urban*
Energy poverty classic (EPC)	1.744%	2.179%	0.958%
Energy poverty median (EPM)	2.257%	2.330%	2.070%
Energy poverty LIHC (EPL)	1.810%	2.028%	1.145%
Fuel and energy poverty median (FPM)	2.626%	2.816%	1.682%
Fuel and energy poverty LIHC (FPL)	2.597%	2.786%	2.004%
Transport poverty LIHC (TPL)	2.530%	2.812%	2.171%
Expenditure quartile 1 (Q1)	1.353%	1.600%	0.619%
Expenditure quartile 4 (Q4)	1.118%	1.332%	0.597%
Total Styrian population	1.274%	1.525%	0.657%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Table 14. Effects (%-change in cost-of-living) of different transfer schemes across energy and fuel poor groups, assuming a carbon tax of EUR 134/tCO_2

Household groups	*NTC*	*FLC*	*INC*	*TGC*	*DEC*	*REC*	*REC$_{GOV}$*
EPC	1.744%	-0.038%	-0.638%	-1.262%	-0.124%	-0.199%	0.061%
EPM	2.257%	1.093%	1.073%	0.768%	0.992%	0.918%	1.018%
EPL	1.810%	-0.158%	-0.830%	-1.682%	-0.303%	-0.323%	0.048%
FPM	2.626%	1.549%	1.582%	1.345%	1.459%	1.390%	1.538%
FPL	2.597%	0.878%	0.256%	-0.411%	0.755%	0.756%	0.927%
TPL	2.530%	0.587%	-0.153%	-0.765%	0.566%	0.542%	0.729%
Expenditure quartile 1	1.353%	-1.450%	-1.888%	-1.882%	-1.561%	-1.660%	-1.534%
Total Styrian population	1.274%	-0.449%	-0.582%	-0.610%	-0.510%	-0.578%	-0.495%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Table 15. Effects (%-change in cost-of-living) of different transfer schemes across energy and fuel poor groups in urban areas, assuming a carbon tax of EUR 77/tCO_2

Household groups in urban areas	*NTC*	*FLC*	*INC*	*TGC*	*DEC*	*REC*	*REC$_{GOV}$*
EPC	0.576%	-0.414%	-0.757%	-1.183%	-0.163%	-0.300%	-0.162%
EPM	1.248%	0.654%	0.670%	0.485%	0.804%	0.722%	0.757%
EPL	0.546%	-0.626%	-1.032%	-1.537%	-0.329%	-0.492%	-0.298%
FPM	1.009%	0.523%	0.472%	0.334%	0.646%	0.578%	0.651%
FPL	1.247%	0.226%	-0.128%	-0.568%	0.484%	0.343%	0.322%
TPL	1.265%	-0.187%	-0.690%	-0.766%	0.181%	-0.020%	0.062%
Expenditure quartile 1	0.369%	-0.398%	-1.850%	-1.663%	-0.950%	-1.052%	-1.195%
Total	0.383%	-0.600%	-0.738%	-0.695%	-0.351%	-0.487%	-0.403%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Table 16. Effects (%-change in cost-of-living) of different transfer schemes across energy and fuel poor groups in rural areas, assuming a carbon tax of EUR 77/tCO_2

Household groups in rural areas	*NTC*	*FLC*	*INC*	*TGC*	*DEC*	*REC*	*REC$_{GOV}$*
EPC	1.362%	0.200%	-0.179%	-0.625%	0.061%	-0.101%	0.126%
EPM	1.523%	0.819%	0.756%	0.573%	0.732%	0.622%	0.710%
EPL	1.248%	0.091%	-0.392%	-0.868%	-0.049%	-0.169%	0.031%
FPM	1.678%	1.045%	1.060%	0.910%	0.969%	0.879%	0.949%
FPL	1.629%	0.611%	0.258%	-0.131%	0.489%	0.381%	0.517%
TLC	1.701%	0.699%	0.312%	-0.079%	0.543%	0.415%	0.573%
Expenditure quartile 1	0.963%	-0.647%	-0.842%	-0.898%	-0.840%	-0.972%	-1.044%
Total	0.923%	-0.069%	-0.131%	-0.157%	-0.188%	-0.319%	-0.282%

Expenditure quartiles are formed based on per capita expenditure, using the OECD-modified equivalence scale.

Table 17. Aggregated results for a carbon tax of EUR 134/tCO₂ with different compensation schemes

	Social Welfare (monthly EUR per household)		*Gini index*	*%-change in cost-of-living*	*Direct Emissions (Mt CO_2 monthly)*		*Total emissions (Mt CO_2 monthly)*	
Baseline	1,506		0.2833	-	0.1819		0.6085	
NTC	1,486	-1.3%	0.2841	1.274%	0.1282	-29.5%	0.5551	-8.8%
FLC	1,514	0.6%	0.2804	-0.449%	0.1292	-28.9%	0.5611	-7.8%
INC	1,516	0.7%	0.2795	-0.582%	0.1293	-28.9%	0.5613	-7.8%
TGC	1,517	0.7%	0.2796	-0.610%	0.1294	-28.8%	0.5616	-7.7%
DEC	1,516	0.7%	0.2801	-0.510%	0.1293	-28.9%	0.5614	-7.7%
REC	1,515	0.6%	0.2802	-0.578%	0.1294	-28.9%	0.5617	-7.7%
REC_{GOV}	1,515	0.6%	0.2802	-0.495%	0.1293	-28.9%	0.5616	-7.7%

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Funding

This research received financial support from the Province of Styria within the call "The Green Transformation: Challenges and Chances".