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Estimating short- and long-run price and income elasticities of final energy demand as a function of household income

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ABSTRACT

This study investigates the short- and long-run price and income elasticities of private households' energy demand, focusing on electricity, heating energy carriers (proxied by natural gas), and car fuels, and examining their variations as a function of household income. Employing longitudinal data from two large private household surveys, we apply method of moments and OLS estimators to fixed and random effects models to capture the dynamic response of energy demand to changes in price and income. Our findings reveal significant heterogeneity in elasticities across different income groups. For electricity, short-run price elasticities range from −0.27 for low-income households to −0.44 for high-income households, with long-run elasticities varying from −0.22 to −0.64. Gas price elasticities show an inverse relationship with income, spanning from −0.64 for low-income to −0.11 for high-income households in the short run, and from −0.58 to −0.15 in the long run. Car fuel price elasticities, which we were not able to differentiate over time, range from −0.47 for low-income to −0.14 for high-income households. Income elasticities also exhibit notable variability. For electricity, short-run income elasticities decrease from 0.048 for low-income households to insignificance for high-income households. Short-run income elasticities of gas demand follow a similar pattern, starting from 0.079 and decreasing with rising income. Contrastingly, income elasticities of car fuel demand increase with income from 0.060 for low-income households to 0.443 for high-income households. Our results underscore the necessity of incorporating socio-economic factors into energy policy design to enhance effectiveness and equity in promoting energy conservation and investments in energy efficiency and electricity generation.

1. Introduction

Private households account for 44 % of the total final energy consumption and 32 % of the total greenhouse gas (GHG) emissions in Germany. The household sector represents 28 % of the total electricity consumption, while the shares in final energy consumption for natural gas and car fuels are even higher with 45 and 60 %, respectively (see Appendix 1). Steering residential energy demand towards energy conservation and low-carbon energy carriers is a key objective of energy policies in Germany to achieve the ambitious climate target of climate neutrality in 2045.

In economics, energy carriers are typically categorized as ordinary and normal goods, meaning their demand decreases as prices rise or income falls. Price elasticity demonstrates that consumption can be reduced by increasing prices, while shifts between energy carriers can be encouraged through changes in relative pricing. While markets inherently apply price signaling to regulate shortages, energy policymakers can leverage this economic principle to design incentive systems that support decarbonization efforts. Complementing this, income elasticity provides insights into how energy consumption adjusts to the general income development or financial relief measures. Together, elasticities offer valuable tools for understanding and influencing energy consumption patterns in pursuit of sustainability goals.

An accurate understanding of energy consumers' responsiveness to price and income changes are required to assess the effectiveness of energy policies. Residential energy consumers are often treated as a homogeneous group with uniform price and income elasticity. However, studies have shown that the responsiveness can vary drastically depending on socioeconomic and sociodemographic factors (cf. Frondel et al., 2019; Khanna et al., 2023; Rehdanz, 2007). Not considering this

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heterogeneity can have severe consequences as a price incentive may lead to intended energy conservation or investments in energy efficiency and electricity generation for one group of consumers (Ito et al., 2018; Kastner and Stern, 2015) whereas other consumers are forced to impose health-threatening consumption restrictions on themselves (cf. Butler and Sherriff, 2017; Liddell and Morris, 2010; Rudge and Gilchrist, 2005).

Recent research has made significant strides in studying energy consumer responsiveness to price and income changes. This comprises insights into the heterogeneity of energy consumers as well as harvesting the advantages of more sophisticated econometric methods. Studies identified among other factors the household income, household composition, settlement type, housing tenure, employment status, the residents' age as well as the age of the dwelling and appliances as significant predictors of electricity, heating energy, or car fuel consumption (cf. Frondel et al., 2012; Khanna et al., 2023; Priesmann et al., 2022; Rehdanz, 2007; Schmitz and Madlener, 2020; Schulte and Heindl, 2017). Regarding the econometric estimation method, dynamic panel data models are preferred due to their ability to address sluggish adjustments of the appliance stock, which can cause price and income responses to occur over time rather than immediately (Trotta et al., 2022). These models employ fixed or random effects to control for unobserved heterogeneity. In contrast, static models, whether using panel or non-panel data, cannot differentiate between short- and long-run elasticities (Alberini et al., 2011). However, by capturing time-dependent effects, dynamic panel data models introduce or exacerbate endogeneity issues by including a lagged dependent variable among the regressors (Alberini and Filippini, 2011). This endogeneity can be mitigated using method of moments estimators (Breitung et al., 2022).

Despite these significant advancements, several key areas in energy consumption research remain underexplored. First, recent studies often focus on single energy carriers, limiting our understanding of comprehensive household energy use patterns. Second, many analyses do not employ longitudinal data or dynamic panel data models and can therefore not account for household-specific effects or differentiate between short- and long-run reactions. Third, when examining continuous socioeconomic factors such as household income, studies typically report only the direction and magnitude of a factor's impact on elasticity, without providing specific elasticities along this moderating socioeconomic factor. Fourth, the saving effects across households with varying numbers of adults and children are frequently overlooked. With our work, we aim to integrate recent advancements in a uniform methodology and assess residential energy consumption patterns across different energy carriers, socioeconomic and sociodemographic conditions, as well as time horizons.

We draw on two large and annually conducted panel data samples, namely the German Socio-Economic Panel (SOEP) and the German Mobility Panel (MOP). The data sets provide information on electricity expenditure from 2010 to 2021, on expenditure on heating energy carriers from 1986 to 2021, and on car fuel consumption from 1994 to 2022, each in combination with a range of household parameters. The SOEP covers around 15,000 households while the MOP currently comprises 1800 households. To account for saving effects across different households, we compute equivalence scales for electricity, heating energy carrier, and car fuel consumption. We then formulate dynamic fixed-effects models for electricity and heating energy carriers and estimate price and income elasticity of demand using a method of moments estimator. Due to data limitations, we use a static random effects model for car fuels that is estimated using an ordinary least squares (OLS) estimator.

In terms of heterogeneity among private households, we use the net household income as a proxy for socioeconomic factors. We add interaction terms to the regression models to represent the impact of income on price and income elasticity as well as on differences between short- and long-run effects of the price and income responsiveness. We then calculate income-dependent elasticities by deriving marginal effects and confidence intervals across the moderating variable net household income.

The remainder of this paper is structured as follows. Section 2 provides background information on the estimation of price and income elasticities. Section 3 details our data sources and preprocessing methods, including the micro samples used, the application of equivalence scales, and the derivation of energy tariffs. Section 4 presents our methodological approach, beginning with general remarks and then elaborating on the models used to estimate price and income elasticities for electricity, heating energy, and car fuel demand. Section 5 reports our findings, presenting the elasticity results for each energy carrier separately, and includes a validation of our results. Finally, Section 6 concludes the paper, summarizing key findings and discussing their policy implications.

2. Background and theoretical framework

2.1. German energy policy context

Germany's energy transition, known as the Energiewende, represents one of the world's most ambitious efforts to transform a national energy system toward climate neutrality. The policy framework is based on the energy policy triangle (Zieldreieck der Energiepolitik), which seeks to balance three fundamental objectives: environmental sustainability, economic affordability, and supply security (Zweifel et al., 2017). Germany has committed to achieving greenhouse gas neutrality by 2045, requiring a comprehensive transformation of energy supply, transport, and demand across all sectors (Bundes-Klimaschutzgesetz, 2019).

The Energiewende has fundamentally altered Germany's energy landscape. Since 1990, total greenhouse gas emissions have been reduced by 46 % through energy efficiency measures and the expansion of renewable energy sources, which now represent a substantial portion of electricity generation (UBA, 2023a; UBA, 2024, 2025; UBA, 2024a). However, this transformation comes with significant challenges. The transition requires massive investments through 2045, covering energy infrastructure adaptation, ensuring supply security, and supporting energy consumers through efficiency measures and technology adoption (Praktiknjo, 2013; Krapp et al., 2024).

The energy transition faces several critical policy challenges that directly affect private households. Carbon pricing mechanisms, such as those through the European Emissions Trading System (EU ETS) and Germany's national emissions trading system (nEHS), create price signals to incentivize decarbonization. However, these uniform price increases disproportionately burden low-income households who spend a larger share of their income on energy and have limited capacity to invest in efficiency improvements or renewable technologies (Priesmann et al., 2022).

Energy poverty has emerged as a pressing concern, with the financial burden of energy costs varying dramatically across income groups (Carley and Konisky, 2020). Social equity considerations permeate multiple aspects of energy policy implementation. Regressive distributional effects have been observed across numerous policy instruments, including the former renewable energy surcharge (EEG-Umlage), network tariffs, and subsidy programs for building renovations and electric vehicles, which predominantly benefit higher-income households capable of making substantial upfront investments (George et al., 2023; Haan et al., 2023; Preuβ et al., 2019; Schlesewsky and Winter 2018).

Understanding how energy demand responds to price and income changes across different income groups is essential for designing effective and equitable energy policies. Uniform policy approaches that treat all households identically can lead to unintended consequences as price incentives may successfully drive energy conservation and efficiency investments among higher-income households while forcing lower-income households to impose health-threatening consumption restrictions on themselves (Butler and Sherriff, 2017; Lambie-Mumford and Snell, 2015).

Income-differentiated elasticity analysis enables policymakers to predict and address these differential impacts. For instance, if low-income households exhibit higher price elasticities for heating energy but lower income elasticities for electricity, targeted policies can be designed accordingly, such as heating assistance programs combined with progressive electricity pricing structures. Furthermore, as Germany implements increasingly stringent carbon pricing and potentially phases out fossil fuel subsidies, understanding income-dependent behavioral responses becomes crucial for designing complementary measures that ensure a socially just transition while maintaining policy effectiveness across all population segments.

2.2. Elasticity theory and concepts

Increases in energy prices do not necessarily result in a proportional increase in energy expenditure. This is due to changes in consumer behavior following such price increases. In general, higher prices lead to lower demand, which also applies to energy carriers. The relationship between the change in the quantity demanded and the change in prices can be expressed mathematically by the (own-) price elasticity of demand ε_p (Mankiw, 2018):

$$\varepsilon^p = \frac{\text{percentage change in demand}}{\text{percentage change in price}} \tag{1}$$

The price elasticity of demand can therefore be interpreted as the relative change in demand (quantity) after a *ceteris paribus* one percent change in the real price. If the elasticity is -2, a one percent price increase leads to a two percent decrease in the quantity demanded. In addition to the own-price elasticity of demand, the cross-price elasticity of demand analogously describes a change in demand for one good as a result of a price change in another good. For example, an increase in heating oil prices can lead to an increase in demand for natural gas.

The higher the (absolute) price elasticity of demand, the more elastic a consumer's demand for a particular good or service. Demand is considered elastic when its absolute price elasticity is above one, meaning that it reacts relatively sensitively to price changes. In contrast, demand with an absolute price elasticity below one is considered inelastic, meaning it is relatively insensitive to price changes (Samuelson and Nordhaus, 2009). In the case of $|\varepsilon_p| = 1$ the quantity demanded and the price change (inversely) proportionally. In the case of inelastic demand functions, an increase in price leads to a rise in total revenue for the supplier, as the decrease in demand is less than the increase in price (Praktiknjo et al., 2011).

Changes in household income also impact the demand for energy carriers, as expressed by income elasticities:

$$\varepsilon^{inc} = \frac{\text{percentage change in demand}}{\text{percentage change in income}} \tag{2}$$

For normal goods, an increase in income leads to a corresponding increase in the demand for these goods, resulting in positive income elasticities.

Suppose households are only partially able to adjust their appliance stocks to external changes (in prices or income) in the short term. These are referred to as short-run elasticity (or the instantaneous effect). In the context of a price change, a price increase ($p_1 \rightarrow p_1'$, Fig. 1 left) changes the price ratio between the prices of goods, resulting in an inward shift of the budget line (cf. B/p_1 and B/p_1'). This triggers a substitution effect with other goods ($x_1^* - x_{1C}^*$) and an income effect due to lower purchasing power ($x_{1C}^* - x_1^{*'}$) (Jin et al., 2021; cf. Praktiknjo, 2014). As a result, the level of utility decreases, but a new equilibrium state does not necessarily arise if the stock of appliances cannot be adjusted in the short run. This can further reduce the level of utility (point B to D). In practical terms, this could mean that households maintain a subsistence level of space heating despite massive price increases and the resulting strong income effect has a negative impact on the consumption of other goods.

In the long run, adjustments to the appliance stock may be possible, for example through investments in energy efficiency, a switch to other energy carriers or a decoupling from price changes through self-generation. If the goods are defined as energy services (such as mobility or heated living spaces), the budget line can shift outwards again (cf. B/p_1'', Fig. 1 right). The same amount of energy services can now be provided with less final energy and thus at lower costs (i.e. the efficiency of the conversion of final energy into useful energy increases) as a result of an investment in energy efficiency. This results in a long-run substitution and income effect ($x_1^* - x_{1F}^*$ and $x_{1F}^* - x_1^{*''}$) and a new equilibrium state (point E). The consumption that occurs in the long run $x_1^{*''}$ can be both larger and smaller than the consumption after the short-run adjustment x_{1D}. In addition, the so-called rebound effect can occur, in which an increase in demand occurs as a result of a decrease in the relative price of a good, thus partially offsetting potential consumption savings brought about by increased efficiency (Herring and Roy, 2007). Such rebound effects may also be heterogeneous among households (Frondel et al., 2012; Kulmer and Seebauer, 2019), with low-income households potentially experiencing larger rebound effects as efficiency improvements enable them to meet previously unmet energy service demands due to financial constraints (Buhl, 2014).

The time frame within which households can adjust to price and income changes is crucial when estimating price and income elasticities using regression models. For static model configurations, it is implicitly assumed that short- and long-run elasticities do not differ (Alberini et al., 2011). In dynamic model configurations, short- and long-run elasticities

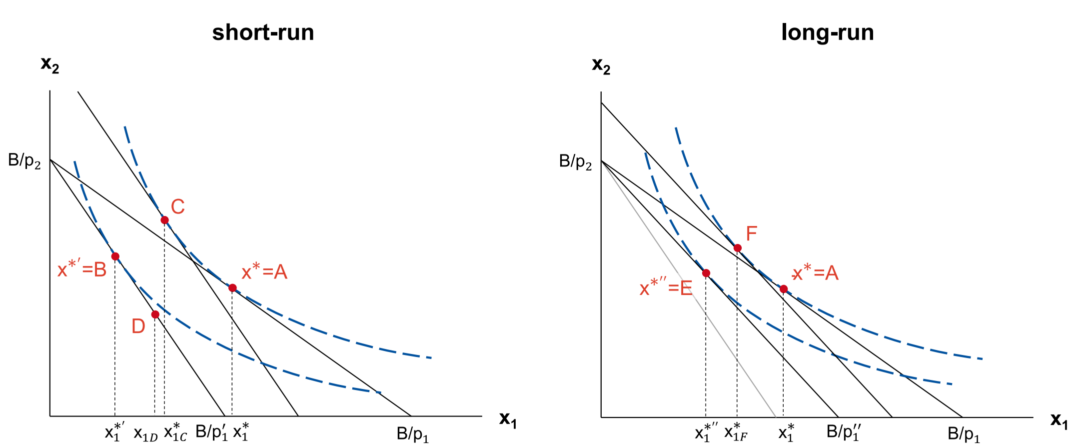

Fig. 1. Short- and long-run effects of a price change.

can be distinguished by introducing a lag term for the dependent variable (here energy consumption). Such a lag term is influenced by the time interval between two surveys. The time interval between two surveys should not exceed the total adjustment period following a price or income change, as this would prevent mapping the time needed to reach the new equilibrium state.

According to microeconomic theory, households make their energy consumption decisions based on marginal costs, i.e. based on the energy price (Zweifel et al., 2017). Household tariffs for electricity and gas (in particular natural gas) in Germany consist of two parts, i.e. a base price and a unit price. Therefore, consumption decisions should be based on the unit price which is the cost of consuming an additional unit of an energy carrier. However, various studies have shown that in complex non-linear tariff models, in which the unit price depends on the amount of consumption (which is the case with block tariffs), consumers' decisions can be better explained by the average costs (i.e. the average unit price, exclusive of the base price) than by the marginal costs (Borenstein, 2009; Ito, 2014; Shaffer, 2020). The regular two-part tariff with a constant unit price is not a complex tariff structure, as the marginal costs are directly known through the unit price. Therefore, in this study, we estimate the price and income elasticities of electricity and gas demand based on marginal prices (i.e. unit prices).

2.3. Methodological contribution and approach

While existing literature has established the theoretical foundations of energy demand elasticities, several methodological gaps remain that this study addresses. First, rather than treating income as a simple control variable, we model elasticities as continuous functions of household income through interaction terms. This allows us to derive specific elasticity values for any income level, rather than just reporting directional effects. Second, we employ bias-corrected method of moments estimators to address the Nickell bias inherent in dynamic panel models with lagged dependent variables, providing more reliable short- and long-run elasticity estimates. Third, unlike studies focusing on single energy carriers, we provide comparable elasticity estimates across electricity, heating, and transport fuels using consistent methodological frameworks. Fourth, we develop and estimate energy carrier-specific equivalence scales rather than relying solely on income-based OECD scales, better capturing household economies of scale in energy consumption. These methodological advances enable more precise policy impact assessments and support the design of income-differentiated energy policies.

3. Data and preprocessing

Our analysis of private households' price and income elasticities of energy demand is based on micro samples that undergo the following preprocessing steps: adjustment of monetary values for inflation using the consumer price index (Destatis, 2024a), equivalization of household parameters to account for saving effects across different household types, and integration of annual energy carrier prices.

3.1. Micro samples

The estimation of elasticities is based on two representative and annually conducted samples of private households in Germany. These are the Socio-Economic Panel (SOEP) of the German Institute for Economic Research (DIW) and the German Mobility Panel (MOP) of the Karlsruhe Institute of Technology (KIT). The survey variables used are listed in Appendix 2.

The SOEP is a representative longitudinal study that has been conducted in Germany since 1984 and is currently funded by the Federal Ministry of Research and Education (BMBF) and the state of Berlin (SOEP Team, 2023). It collects data from around 15,000 private households (and thus ~0.04 % of all German private households) on various socio-economic aspects on the household and individual levels. The SOEP survey takes place annually and is conducted by the Institute for Applied Social Sciences (infas). The most recent survey used in this study dates from 2021 and was published in 2023. The SOEP households are selected using a multi-stratified random sample at the federal, state, and municipal levels. To avoid underrepresentation of groups, additional subsamples are carried out for immigrants and particularly high-income households.

The MOP is a longitudinal study on the mobility behavior of German private households that has been conducted annually since 1994 (Vallée et al., 2022). Over 1800 households (0.004 % of German private households) are surveyed on behalf of the Federal Ministry for Digital and Transport Affairs (BMDV). The MOP surveys are conducted as a rotating panel in which households are surveyed repeatedly over three consecutive years. In addition to household characteristics such as household composition or household income, the travel and fuel log also asks for information on household transportation activities. The results of the current survey for 2021 and 2022 were published at the end of 2022. The selection of households for the MOP is based on quotas for four household types and a distinction between households with and without a car.

In Table 1, the SOEP and MOP are compared to the larger but less frequently conducted income and consumption sample of the German Research Data Center of the Federal Statistical Office and the Statistical Offices of the Federal States (FDZ, 2020). The two samples represent the population of private households in Germany with varying degrees of accuracy. Therefore, when extrapolating the results to the population, private households must be weighted using extrapolation factors which are provided by the samples. The extrapolation can be applied based on the following relationship:

$$X_{ges} = \sum_{i}^{N} \rho_i {}^* x_i, \tag{3}$$

where X_{ges} is the total value of a variable extrapolated to Germany (e.g. expenditure on energy carrier), ρ_i is the extrapolation factor (weight) of household i, x_i is the unweighted value of the variable for household i and N is the number of households in the sample.

3.2. Equivalence scales

If energy carriers are shared among household members, they benefit from economies of scale, as larger households can use energy more efficiently than smaller households. The same applies to household income, where a family of four does not need four times as much as a single-person household to achieve a comparable standard of living. A per capita attribution of income or expenditure does not reflect these savings effects. To adequately compare households with one another, the prevailing economies of scale must therefore be taken into account. Also, household composition may change over time, leading to price- and income-independent consumption changes. This is accounted for using equivalization that applies weighting based on the household composition. We develop different weighting methods for household income as well as expenditure on electricity, heating energy carriers (in our case natural gas), and car fuels (in our case petrol and diesel) to reflect commodity-specific economies of scale. To calculate household equivalents for a household i, the variables applicable to the entire household x_i^{total} are divided by their corresponding equivalence value λ_i^{ef}:

$$x_i^{hh.-equ.} = \frac{x_i^{total}}{\lambda_i^{ef}} \tag{4}$$

Household income is weighted using the modified OECD equivalence scale (OECD, 2013). This assigns an equivalence value of 1.0 to the main income earner, 0.5 to other household members aged 14 and over, and

Table 1
Descriptive comparison of the EVS, SOEP, and MOP samples.

	EVS	SOEP		MOP	
Survey characteristics					
Survey year	2018	2018[a]	2021[a]	2018[b]	2021[b]
period	Jan–Dec.	Jan–Dec.	Jan–Dec.	Apr–Jun.	Apr–Jun.
duration	3 months	1 day	1 day	1 week	1 week
Population [in 1.000 private households]	40.805	40.805	40.974	40.805	40.974
Sample size [in private households]					
total	80.762	18.681	13.697	1.845	1.840
adjusted sample	42.226	18.681	13.697	1.845	1.840
People					
Gender					
female	52,8 %	50,1 %	49,8 %	49,7 %	50,3 %
male	47,2 %	49,9 %	50,2 %	50,3 %	49,7 %
Age [in years]					
under 18	17,5 %	28,9 %	26,0 %	14,1 %	13,6 %
18–45	29,2 %	34,6 %	33,4 %	22,7 %	21,9 %
46–65	31,8 %	24,2 %	26,7 %	37,7 %	39,0 %
66 and older	21,5 %	12,3 %	13,9 %	25,5 %	25,5 %
Households					
Household size [in persons]					
1	33,4 %	26,5 %	27,9 %	36,0 %	31,1 %
2	40,7 %	31,4 %	33,4 %	38,8 %	43,0 %
3	12,4 %	13,9 %	13,2 %	12,2 %	12,2 %
4	10,3 %	14,9 %	14,2 %	9,3 %	10,9 %
5 and more	3,1 %	13,4 %	11,3 %	3,6 %	2,8 %
Household type					
single	33,4 %	26,5 %	28,7 %	36,1 %	31,3 %
single parent	5,0 %	9,6 %	8,2 %	1,6 %	1,9 %
couple without children	35,8 %	25,1 %	26,7 %	37,6 %	41,8 %
couple with children	22,3 %	35,5 %	32,1 %	13,7 %	13,1 %
other	3,6 %	3,3 %	4,4 %	11,0 %	12,0 %
Net household income (nominal) [in EUR/year]					
under 12,000	5,0 %	8,9 %	12,0 %	5,7 %	3,3 %
12,000 to under 24,000	16,5 %	22,9 %	19,5 %	22,9 %	15,2 %
24,000 to under 36,000	19,3 %	22,8 %	20,9 %	23,6 %	22,6 %
36,000 to under 48,000	17,0 %	17,0 %	17,2 %	20,7 %	22,4 %
48,000 to under 60,000	13,4 %	11,6 %	11,3 %	12,3 %	14,0 %
60,000 and more	28,8 %	16,8 %	19,3 %	14,8 %	22,5 %

Possible rounding errors are display-related.
[a] Net household income in the SOEP for 2018 is based on the data from 2019 on the previous year's income. As no survey on the previous year's income is yet available for 2022, the reported current monthly net household income is used instead for 2021. This leads to an underestimation of net household income in the SOEP statistics for 2021.
[b] Surveys always refer to two consecutive years, for example, 2018/2019. The household data is collected in the first year, i.e. in 2018 for the 2018/2019 survey.

0.3 to household members aged under 14. A four-person household with two adults and two children aged under 14 thus receives a total equivalence value of $1.0 + 0.5 + 2\cdot 0.3 = 2.1$ (see Table 2).

Schulte and Heindl (2017) demonstrated that the OECD equivalence scale is only partially suitable for weighting expenditure on electricity and heating energy carriers. We assume that the same applies to expenditure on car fuels. New equivalence values are therefore estimated for expenditure on these energy carriers using a regression approach.

For electricity and heating energy carriers, the equivalence values are calculated analogously to the OECD equivalence scale based on the number of household members aged 14 and over ($x_{i,t}^{\#res.\geq 14}$) and under 14 years of age ($x_{i,t}^{\#res.\ <14}$). The SOEP data are used for the estimation and a regression approach is applied. Using equation (5), separate regressions are performed for electricity and natural gas. The regression coefficients β_1^{ef} and β_2^{ef} are combined according to see equation (6) to form the total

Table 2
Equivalence values according to the modified OECD equivalence scale.

Equivalence values		Number of residents under 14 years of age				
		0	1	2	3	4
Number of residents aged 14 and over	1	1.0	1.3	1.6	1.9	2.1
	2	1.5	1.8	2.1	2.4	2.7
	3	2.0	2.3	2.6	2.9	3.2
	4	2.5	2.8	3.1	3.4	3.7

Table 3
Equivalence values for electricity expenditure.

Electricity equivalence values		Number of residents under 14 years of age				
		0	1	2	3	4
Number of residents aged 14 and over	1	1.000	1.174	1.347	1.521	1.695
	2	1.240	1.414	1.588	1.762	1.935
	3	1.481	1.655	1.828	2.002	2.176
	4	1.721	1.895	2.069	2.242	2.416

Table 4
Equivalence values for expenditure on heating energy carriers (in our case natural gas).

Heating energy carriers equivalence values		Number of residents under 14 years of age				
		0	1	2	3	4
Number of residents aged 14 and over	1	1.000	1.086	1.173	1.259	1.345
	2	1.130	1.216	1.303	1.389	1.475
	3	1.260	1.346	1.432	1.519	1.605
	4	1.389	1.476	1.562	1.648	1.735

equivalence factor λ^{ef}.

$$\frac{e_{i,t}}{\overline{e}_{single}} = 1 + \beta_1^{ef} * \left(x_{i,t}^{\#res.\geq 14} - 1\right) * + \beta_2^{ef} * x_{i,t}^{\#res. \ < 14} + \tau_t + u_{i,t} \tag{5}$$

$$\lambda^{ef} = 1 + \beta_1^{ef} * \left(x_{i,t}^{\#res.\geq 14} - 1\right) * + \beta_2^{ef} * x_{i,t}^{\#res. \ < 14} \tag{6}$$

The inflation-adjusted expenditure on an energy carrier $e_{i,t}$ of a household i at time t are first divided by the corresponding average expenditure of a single-person household. This ratio corresponds to the factor by which the energy consumption of a household deviates from an average one-person household. As the base case is a single-person household, only the additional household members aged 14 and over are included in the calculation ($x_{i,t}^{\#res.\geq 14} - 1$). By means of τ_t, the fixed annual effects are controlled and $u_{i,t}$ denotes the idiosyncratic error term. The regression models are determined using OLS estimators.

Tables 3 and 4 show the resulting estimates for the equivalence values for expenditure on electricity and natural gas (the latter is used to represent heating energy carriers). It is noticeable that both the equivalence values for electricity and natural gas are significantly lower than the factors according to the OECD scale. An example of this is a four-person household with two children under the age of 14. While the household is assigned an equivalence factor of 2.1 according to the OECD scale, this is 1.588 for the estimated electricity scale and 1.303 for the estimated natural gas scale. The results are therefore in line with those of Schulte and Heindl (2017) in that scaling the expenditure for electricity and natural gas according to the OECD scale would lead to an underestimation of the economies of scale. It is also confirmed that the economies of scale for electricity expenditure are lower than those for natural gas as household size increases.

To determine the equivalence factors for expenditure on car fuel (represented by gasoline and diesel), the number of household members aged 18 and over ($x_{i,t}^{\#res.\geq 18}$) who potentially have a driving license and the number of household members under the age of 18 ($x_{i,t}^{\#res. \ < 18}$) are used.

$$\frac{e_{i,t}}{\overline{e}_{single}} = 1 + \beta_1^{ef} * \left(x_{i,t}^{\#res.\geq 18} - 1\right) * + \beta_2^{ef} * x_{i,t}^{\#res. \ < 18} + \tau_t + u_{i,t} \tag{7}$$

$$\lambda^{ef} = 1 + \beta_1^{ef} * \left(x_{i,t}^{\#res.\geq 18} - 1\right) * + \beta_2^{ef} * x_{i,t}^{\#res. \ < 18} \tag{8}$$

The inflation-adjusted expenditure on car fuels $e_{i,t}$ of a household i at time t is divided by the corresponding average expenditure of a single-person household $\overline{e}_{single}$. According to this base case, only the additional household members aged 18 and over are included in the calculation ($x_{i,t}^{\#res.\geq 18} - 1$). Table 5 shows the results for the estimates of the equivalence values for car fuel expenditure.

The estimated equivalence values are compared to the OECD equivalence scale in Appendix 3.

Table 5
Equivalence values for the expenditure on car fuels for private household transportation (in our case gasoline and diesel).

Car fuel equivalence values		Number of residents under the age of 18			
		1	2	3	4
Number of residents aged 18 and over	1	1.000	1.215	1.430	1.646
	2	1.450	1.665	1.881	2.096
	3	1.900	2.116	2.331	2.546
	4	2.351	2.566	2.781	2.996

3.3. Energy tariffs

The missing information on energy tariffs in the SOEP sample is allocated externally for electricity and natural gas. Only the MOP sample contains information on the prices paid for the reported refueling processes. The relationship between the reported energy expenditure e_i of a household i, consumption c_i, the base price p_i^{base} (which is independent of the consumed quantity, only valid for grid-bound supply of electricity and gas), and a unit price p_i^{unit} is as follows:

$$e_i = p_i^{base} + p_i^{unit} * c_i \tag{9}$$

Energy tariffs for private households are based on the consumer price data of the Federal Statistical Office on electricity and natural gas tariffs (Destatis, 2024b), data on the development of electricity and natural gas prices from the German Association of Energy and Water Industries (BDEW, 2024a, 2024b), and data on the development of mineral oil prices from the European Commission (2024). To break down the average prices of electricity and natural gas tariffs, an annual base price of EUR 139 for electricity tariffs and EUR 154 for gas tariffs is assumed, both at May 2023 prices (Neubauer, 2023). These are applied to earlier years by adjusting for inflation. Finally, the unit prices for electricity and gas are scaled by comparing the total consumption of electricity and gas resulting from the reported energy expenditure of households and the assigned unit price with the total annual consumption according to data provided by AG Energiebilanzen (AGEB, 2023).

The resulting tariff assumptions used in this study are shown in Fig. 2 (see Appendix 4 for a tabular representation). Electricity and gas tariffs are differentiated by federal state based on differences in grid charges (average final energy prices are shown). In addition, it is assumed that the same energy tariffs apply to all private households.

4. Model

4.1. General methodological remarks

As the EVS and SOEP data indicate expenditure rather than consumption of energy carriers, the missing consumption figures c for electricity and heating energy carriers are subsequently calculated as annual expenditure e minus the annual base price p^{base} divided by the unit price p^{unit}:

$$c = \frac{e - p^{base}}{p^{unit}} \tag{10}$$

Based on the energy consumption of households, regression models are set up that relate the dependent variable (energy consumption) to several independent variables (including energy carrier unit price and income). A generalized log-log-transformed regression equation with dynamic model configuration is shown below:

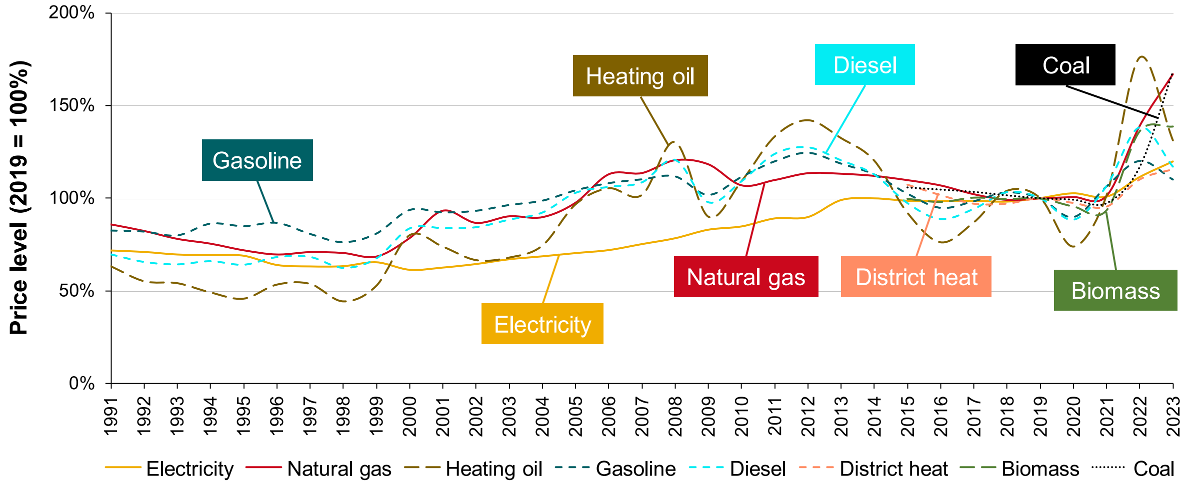

Fig. 2. Development of the real average final energy price level for private households from 1991 to 2023 (2019 = 100 %). Own illustration based on data from BDEW (2024a, 2024b), Destatis (2024b), the European Commission (2024) and AGEB (2023).

$$\ln(c_{i,t}) = \beta^{c_{t-1}} \ln(c_{i,t-1}) + \beta^{c_{t-1}\cdot inc} \ln(EC_{i,t-1}) \ln(inc_{i,t}) + \beta^{p} \ln(p_t^{unit}) + \beta^{inc} \ln(inc_{i,t}) + \beta^{p\cdot inc} \ln(p_t^{unit}) \ln(inc_{i,t}) + \beta^{inc^2} \ln(inc_{i,t})^2 + \beta_X^T x_{i,t} + \gamma_i + u_{i,t}, \qquad (11)$$

where i stands for one of N households and t for one year from the observation period over T years. The energy consumption $(c_{i,t})$ is the dependent variable which set in relation to the independent variables of consumption from the previous year $(c_{i,t-1})$, the unit price (p_t^{unit}), the net equivalized household income $(inc_{i,t})$, and other household covariates $(x_{i,t})$. γ_i representsthe fixed household effects and $u_{i,t}$ denotes the idiosyncratic error term.

Our model introduces an interaction term between unit price and net equivalized household income to capture income-dependent price elasticities: $\ln(p_t^{unit}) \cdot \ln(inc_{i,t})$. Based on the regression coefficients of the unit price (β^p) and this interaction term, the short-run income-dependent price elasticities of energy demand $\varepsilon_{i,t}^{p,SR}$ can be determined by partial derivation according to Cramer (1973) as follows:

$$\varepsilon_{i,t}^{p,SR} = \beta^{p} + \beta^{p\cdot inc} \cdot \ln(inc_{i,t}), \qquad (12)$$

where *SR* stands for *short-run*. To estimate an income-dependent income elasticity, we include a squared income term: $\ln(inc_{i,t})^2$. For SOEP-based estimates, we derive long-run elasticities by introducing an income-dependent lag term through an additional interaction variable: $\ln(c_{t-1}) * \ln(inc_{i,t})$. In contrast, for MOP-based estimates, we employ a static model without a lag term, as the panel's maximum household representation period of three years is insufficient for estimating long-run effects. The short-run income-dependent income elasticity of energy demand $\varepsilon_{i,t}^{inc,SR}$ can be calculated from mean values of unit prices $(\overline{p^{unit}})$ and the energy consumption of the previous period $(\overline{c_{t-1}})$:

$$\varepsilon_{i,t}^{inc,SR} = \beta^{inc} + \beta^{p\cdot inc} \cdot \ln(\overline{p^{unit}}) + \beta^{c_{t-1}\cdot inc} \cdot \ln(\overline{c_{t-1}}) + 2 \cdot \beta^{inc^2} \cdot \ln(inc_{i,t}) \qquad (13)$$

The income-dependent lag term $\theta_{i,t}$ is calculated analogously to equation (12):

$$\theta_{i,t} = \beta^{c_{t-1}} + \beta^{c_{t-1}\cdot inc} \cdot \ln(inc_{i,t}) \qquad (14)$$

The long-run price $(\varepsilon_{i,t}^{p,LR})$ and income $(\varepsilon_{i,t}^{inc,LR})$ elasticities can be derived from their short-run counterparts using the lag term coefficient $(\theta_{i,t})$ as follows (cf. Pesaran and Smith, 1995):

$$\varepsilon_{i,t}^{p,LR} = \frac{\varepsilon_{i,t}^{p,SR}}{1 - \theta_{i,t}}, \qquad (15)$$

$$\varepsilon_{i,t}^{inc,LR} = \frac{\varepsilon_{i,t}^{inc,SR}}{1 - \theta_{i,t}}, \qquad (16)$$

where *LR* stands for *long-run.*

In our case, short-run price and income elasticities capture consumer

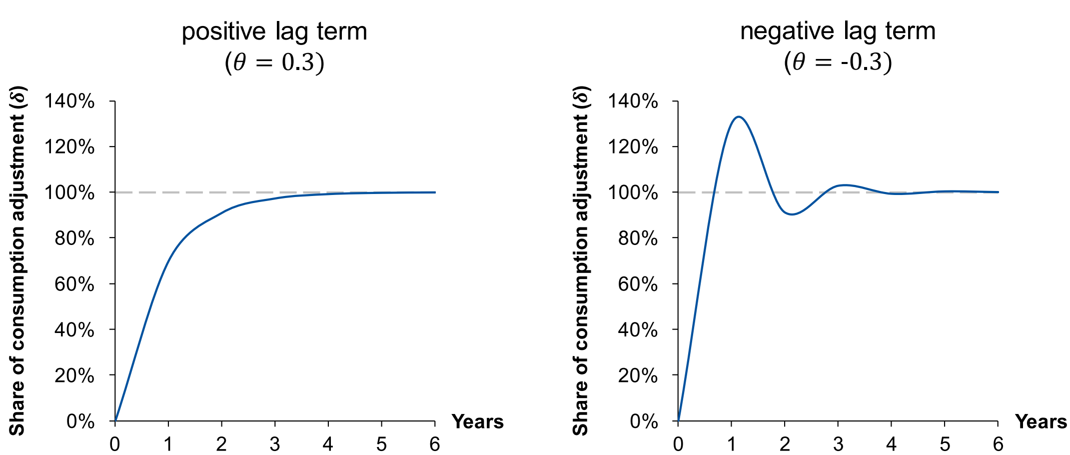

Fig. 3. Proportions of the total long-run realized consumption adjustment as a response to a price or income change.

responses to price and income changes within one year, whereas the duration of long-run effects varies based on the magnitude of the lag term coefficient. Total long-run consumption changes are distributed over multiple years following the initial price or income change. In the short run, i.e. within one year, a proportion $\delta = 1 - \theta$ is realized, where θ represents the lag term:

$$\delta_0 = 1 - \theta \tag{17}$$

In the second year, consumption is determined by a proportion of θ of the previous year's consumption, which in turn includes a share of $1-\theta$ of the total consumption adjustments to the initial price or income change. This pattern continues in subsequent years, with the assumption that 100 % of consumption adjustments are eventually realized in the long run, as consumption converges to a new equilibrium state. The cumulative proportion of total consumption adjustments realized by a given year n can be expressed using a geometric series:

$$\sum_{t=0}^{\infty} \delta_t = (1-\theta) + (1-\theta)\cdot\theta + (1-\theta)\cdot\theta^2 + \ldots = (1-\theta)\cdot\sum_{t=0}^{\infty}\theta^t = \frac{1-\theta}{1-\theta} = 1 \tag{18}$$

$$\delta_{t\geq 1} = \delta_{t-1} + \theta^t\cdot(1-\theta) \tag{19}$$

Fig. 3 shows the cumulative proportions of the total consumption adjustment calculated for two exemplary lag terms θ over a period of six years.

To avoid the nickel bias in the dynamic panel regressions for electricity and gas, which can lead to a bias in the estimator for the lag term $\beta^{c_{t-1}}$, the STATA function *xtdpdbc* is used to estimate the models, which implements a bias-corrected method of moments estimator (Breitung et al., 2022). The static model for car fuels is estimated using the STATA-function *xtreg*. To address possible heteroscedasticity and autocorrelation, clustered and robust standard errors are used (Stock and Watson, 2008).

For the income-dependent variables, the coefficients (i.e. marginal effects), as well as corresponding standard errors and confidence intervals are determined along the moderating variable (net equivalized household income) using the delta method. Brambor et al. (2006) argue that the significance of the interaction term between two regressors does not allow any interpretation of the significance of the overall effect, as this depends on the value of the moderating variable, i.e. the variable fixed in an evaluation. The marginal effects, standard errors, and confidence intervals are calculated using the STATA *margins* function. The effect of the price or income on consumption is significant if both the upper and lower limits of the confidence interval are either above or below zero. Finally, the long-run elasticities and associated standard errors are calculated using the STATA function *nlcom*.

4.2. Price and income elasticities of electricity demand

The estimation of the short- and long-run price and income elasticities of electricity demand is based on the SOEP household sample. The SOEP contains annual data on expenditure on electricity from 2010 to 2021. To avoid distortions due to the COVID-19 pandemic-related structural changes in electricity demand in 2020 and 2021, data is limited to the years 2010–2019. After excluding all households without information on electricity expenditure or income and that contain other relevant data gaps, the panel sample used for the estimation contains 53,742 observations from 9046 households. Table 6 shows the descriptive statistics of the sample.

A Hausman test was carried out to specify the model type. The null hypothesis that the individual effects (in this case of households) do not correlate with the independent variables of the model (Hausman, 1978) was rejected and a fixed effects model was selected.

Let $c_{i,t}^{el}$ be the annual electricity consumption of a household i at time t, $p_t^{el,unit}$ the unit price for electricity at time t, and $inc_{i,t}$ the annual net equivalized household income, then the model configuration used is as follows:

Table 6
Descriptive statistics for the sample for estimating elasticities of electricity demand based on SOEP data and own calculations.

Variable	Mean value	Standard deviation	Min	Max
Annual equivalized electricity consumption in kWh	2325	1263	6	34,673
Real (2003 = 100) unit price ($p^{el,unit}$) in EUR-ct/kWh	18.61	0.90	15.95	19.32
Real (2003 = 100) net equivalized household income (inc) in EUR	18,276	15,160	128	991,418
Equivalized living space in m^2	54.37	20.76	8.00	300.00
Household type				
One-person household	0.28	0.45	0.00	1.00
Single parent	0.24	0.43	0.00	1.00
Couple without children	0.31	0.46	0.00	1.00
Couple with children	0.15	0.36	0.00	1.00
Other household	0.02	0.13	0.00	1.00
At least one university degree available	0.29	0.45	0.00	1.00
At least one household member employed	0.69	0.46	0.00	1.00
Year of construction of the residential building				
before 1949	0.23	0.42	0.00	1.00
from 1949 and before 1990	0.62	0.49	0.00	1.00
from 1990 and before 2001	0.10	0.30	0.00	1.00
from 2001	0.06	0.23	0.00	1.00
Housing tenure				
Owner	0.11	0.31	0.00	1.00
Tenant	0.89	0.32	0.00	1.00
Other housing tenure	0.00	0.04	0.00	1.00
Residential building type				
One/two-family house	0.24	0.43	0.00	1.00
Apartment building	0.66	0.48	0.00	1.00
Other building type	0.10	0.30	0.00	1.00
Average age of adult household members in years	48.33	16.43	19.00	100.00
Electric heating	0.04	0.20	0.00	1.00
Electric water heating	0.19	0.39	0.00	1.00
Air conditioning	0.01	0.11	0.00	1.00
Photovoltaic system or solar panels	0.05	0.21	0.00	1.00

Possible rounding errors are display-related.

Table 7
Descriptive statistics for the sample for estimating elasticities of demand for heating energy carriers based on SOEP data and own calculations.

Variable	Mean value	Standard deviation	Min	Max
Annual equivalized natural gas consumption in kWh	14,475	8539	19	139,967
Real (2003 = 100) unit price for natural gas ($p^{gas,unit}$) in EUR-ct/kWh	5.25	0.96	3.54	6.63
Real (2003 = 100) net equivalized household income (inc) in EUR	19,550	16,874	128	991,418
Equivalized living space in m^2	56.06	22.01	6.67	280.00
Household type				
One-person household	0.24	0.43	0.00	1.00
Single parent	0.29	0.45	0.00	1.00
Couple without children	0.35	0.48	0.00	1.00
Couple with children	0.09	0.29	0.00	1.00
Other household	0.02	0.14	0.00	1.00
At least one university degree available	0.28	0.45	0.00	1.00
At least one household member employed	0.69	0.46	0.00	1.00
Year of construction of the residential building				
before 1949	0.33	0.47	0.00	1.00
from 1949 and before 1990	0.52	0.50	0.00	1.00
from 1990 and before 2001	0.12	0.32	0.00	1.00
from 2001	0.03	0.18	0.00	1.00
Housing tenure				
Owner	0.25	0.43	0.00	1.00
Tenant	0.75	0.43	0.00	1.00
Other housing tenure	0.00	0.02	0.00	1.00
Residential building type				
One/two-family house	0.37	0.48	0.00	1.00
Apartment building	0.60	0.49	0.00	1.00
Other building type	0.04	0.19	0.00	1.00
Average age of adult household members in years	48.42	16.16	19.00	99.00

Possible rounding errors are display-related.

$$\ln\left(c_{i,t}^{el}\right) = \beta^{c_{t-1}} \ln\left(c_{i,t-1}^{el}\right) + \beta^{c_{t-1}\cdot inc} \ln\left(c_{i,t-1}^{el}\right)\ln\left(inc_{i,t}\right) + \beta^{p} \ln\left(p_t^{el,unit}\right) + \beta^{inc} \ln\left(inc_{i,t}\right) + \beta^{p\cdot inc} \ln\left(p_t^{el,unit}\right)\ln\left(inc_{i,t}\right) + \beta^{inc^2} \ln\left(inc_{i,t}\right)^2 + \boldsymbol{\beta}_{\boldsymbol{X}}^{\boldsymbol{T}} \boldsymbol{x}_{\boldsymbol{i},\boldsymbol{t}} + \gamma_i + u_{i,t} \tag{20}$$

The regression coefficients of the unit price, β^{p}, the net equivalized household income, β^{inc}, their interaction term, $\beta^{p\cdot inc}$ and the squared income, β^{inc^2}, enable the derivation of income-dependent elasticities. The regression coefficient $\beta^{c_{t-1}}$ and the interaction term with income $\beta^{c_{t-1}\cdot inc}$ represent the income-dependent coefficient of the lagged electricity consumption. The household characteristics are controlled by means of the vector of household covariates $\boldsymbol{x}_{i,t}$, γ_i represents the household fixed effects, and $u_{i,t}$ denotes the idiosyncratic error term. No year fixed effects are used, as the unit price is constant annually across all households, and including fixed annual effects would prevent a meaningful interpretation of the unit price's regression coefficient. The selection of household covariates is based on a combined and extended literature-based set of characteristics (c.f. Alberini et al., 2011; Besagni and Borgarello, 2019, 2018; Filippini, 2011; Frondel et al., 2019; Rehdanz, 2007; Schulte and Heindl, 2017).

4.3. Price and income elasticities of demand for heating energy carriers

The estimation of the short and long-run price and income elasticities of demand for heating energy carriers is again based on the SOEP household sample. The SOEP contains annual data on expenditure on heating energy carriers from 1986 to 2021. The survey years used for the estimation are limited to the years after the German reunification in 1991. In addition, the years 2020 and 2021 are again excluded to avoid

Table 8
Descriptive statistics for the sample to estimate elasticities of demand for motive power based on MOP data and own calculations.

Variable	Mean value	Standard deviation	Min	Max
Annual equivalized car fuel consumption in liters	964	649	44	8420
Real (2003 = 100) annual average car fuel price ($p^{car\ fuel}$) in EUR-ct/liter	116.87	13.43	73.44	183.68
Real (2003 = 100) annual net equivalized household income (inc) in EUR	19,021	7275	908	54,285
Region type				
Inner city area, large city	0.09	0.28	0.00	1.00
Outskirts, big city	0.18	0.39	0.00	1.00
Inner city area, medium-sized city	0.07	0.25	0.00	1.00
Outskirts, medium-sized city	0.17	0.37	0.00	1.00
Small town	0.24	0.43	0.00	1.00
Rural area	0.26	0.44	0.00	1.00
Household type				
Small household with working people	0.40	0.49	0.00	1.00
Small household without employees	0.33	0.47	0.00	1.00
Household with children under 18	0.18	0.39	0.00	1.00
Household without children, 3 or more adults	0.08	0.27	0.00	1.00
At least one university degree available	0.28	0.45	0.00	1.00
At least one household member employed	0.64	0.48	0.00	1.00
Average age of adult household members in years	55.66	14.01	19.00	91.00
Average age of vehicles in years	7.82	5.07	0.00	39.00
Average horsepower of the vehicles	113.56	42.30	10.00	930.00

Possible rounding errors are display-related.

Table 9
Regression results for the estimation of price and income elasticities of electricity demand.

	Coefficient	Standard error	[95 % confidence interval]	
$\ln(c^{el}_{t-1})$	−1.798[a]	(0,018)	−1834	−1763
$\ln(c^{el}_{t-1})*\ln(inc)$	0.191[a]	(0,002)	0,187	0,195
$\ln(p^{el,unit})$	0.221	(0,775)	−1297	1739
$\ln(inc)$	−1.097[a]	(0,283)	−1652	−0,541
$\ln(p^{el,unit})*\ln(inc)$	−0.06	(0,08)	−0,216	0,097
$\ln(inc)^2$	−0.008	(0,007)	−0,023	0,006
ln(living space)	0.348[a]	(0,021)	0,307	0,39
Household type (Ref.: single-person household)				
Single parent	0.189[a]	(0,017)	0,156	0,222
Couple without children	0.229[a]	(0,02)	0,191	0,268
Couple with children	0.172[a]	(0,019)	0,135	0,209
Other household	0.157[a]	(0,032)	0,095	0,219
At least one university degree available (Ref.: No)				
Yes	0.015	(0,027)	−0,039	0,068
At least one household member employed (Ref.: No)				
Yes	0.013*	(0,008)	−0,001	0,028
Year of construction of the residential building (Ref.: before 1949)				
from 1949 and before 1990	−0.021	(0,016)	−0,053	0,011
from 1990 and before 2001	−0.007	(0,023)	−0,052	0,039
from 2001	−0.044[b]	(0,026)	−0,095	0,007
Housing tenure (Ref.: Owner)				
Tenant	0.016	(0,023)	−0,028	0,061
Other housing tenure	−0.123	(0,129)	−0,375	0,129
Residential building type (Ref.: single/two-family house)				
Apartment building	−0.039[a]	(0,011)	−0,062	−0,017
Other building type	−0.057[a]	(0,01)	−0,077	−0,037
Average age of adult household members	−0.001	(0,001)	−0,002	0,001
Electric heating (Ref.: Not available)				
Available	0.032	(0,021)	−0,01	0,074
Electric water heating (Ref.: Not available)				
Available	0.021[b]	(0,011)	−0,001	0,043
Air conditioning (Ref.: Not available)				
Available	−0.026	(0,023)	−0,072	0,019
Photovoltaic system or solar panels (Ref.: Not available)				
Available	−0.027	(0,019)	−0,064	0,01
Dummy variable per federal state	Yes			
Time effects	No			
Budget effects	Yes			
Number of observations	53,742			
Number of households	9046			
R^2 (corrected $R)^2$	0.2081 (0.2075)			
F-statistics	878.42[a]			

Clustered robust standard errors in brackets.
**$p < 0.05$.
[a] $p < 0.01$.
[b] $p < 0.1$.

distortions due to structural changes caused by the COVID-19 pandemic. This results in a total observation period from 1991 to 2019.

The study is limited to households with natural gas-fired heating systems. On average, natural gas heating systems are the most widespread in the residential building sector over the sample period. In addition, limiting the study to one type of heating system makes it possible to compare the reactions to price changes between households, as the prices for different heating energy carriers such as natural gas, heating oil, or electricity can differ substantially. Rehdanz (2007) tested estimating elasticities of different energy carrier demands using information on the energy density, but all the models tested resulted in misspecifications. Households receiving basic income support are excluded from the analysis, as heating expenses are covered by social benefits (§ 22 SGB 2, 2003).

The panel sample used for the estimation contains 50,165 observations from 6138 households, excluding households without natural gas heating and those without information or with data gaps on expenditure on heating energy carriers and income. Table 7 shows the descriptive statistics of the sample.

A Hausman test was again applied to the results of an estimation model with fixed effects and one with random effects. The null hypothesis that the individual effects of the households do not correlate with the independent variables of the model is rejected, which leads to a decision of a fixed effects model.

Let $c^{gas}_{i,t}$ be the natural gas consumption of a household i at time t, $p^{gas,unit}_t$ the unit price for natural gas at time t and $inc_{i,t}$ the net equivalized household income i at time t, then the model configuration used is as follows:

$$\ln\left(c^{gas}_{i,t}\right) = \beta^{c_{t-1}} \ln\left(c^{gas}_{i,t-1}\right) + \beta^{c_{t-1}\cdot inc} \ln\left(c^{gas}_{i,t-1}\right)\ln\left(inc_{i,t}\right) + \beta^{p}*\ln\left(p^{gas,unit}_t\right) + \beta^{inc}*\ln\left(inc_{i,t}\right) + \beta^{p\cdot inc} \ln\left(p^{gas,unit}_t\right)\ln\left(inc_{i,t}\right) + \beta^{inc^2} \ln\left(inc_{i,t}\right)^2 + \boldsymbol{\beta}^T_{\boldsymbol{X}}\boldsymbol{x}_{i,t} + \gamma_i + u_{i,t} \tag{21}$$

In contrast to other studies, heating degree days are not used as explanatory variables. Most households surveyed in the SOEP in the period 1991 to 2019 live in rented accommodation (58 %) and only report their expenditure on heating energy carriers for the current year. In contrast, the proportion of households in owner-occupied housing (42 %) report their expenditure retrospectively for the previous year. As the influence of the heating degree days can only be recorded with the annual statement in the form of repayments or additional payments, the

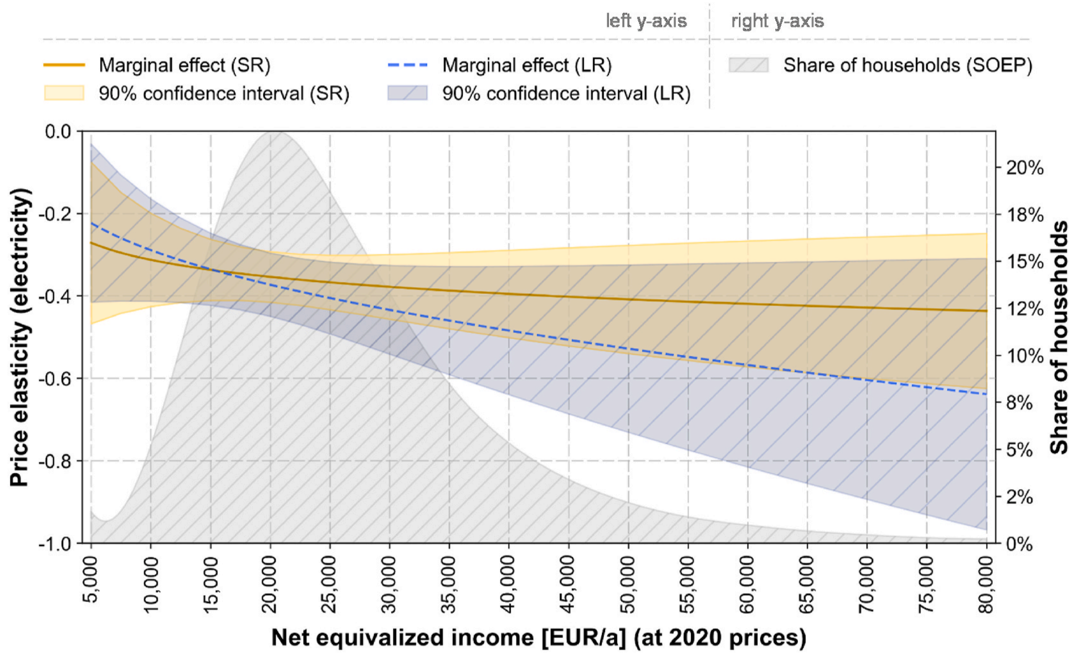

Fig. 4. Income-dependent price elasticities of electricity demand.

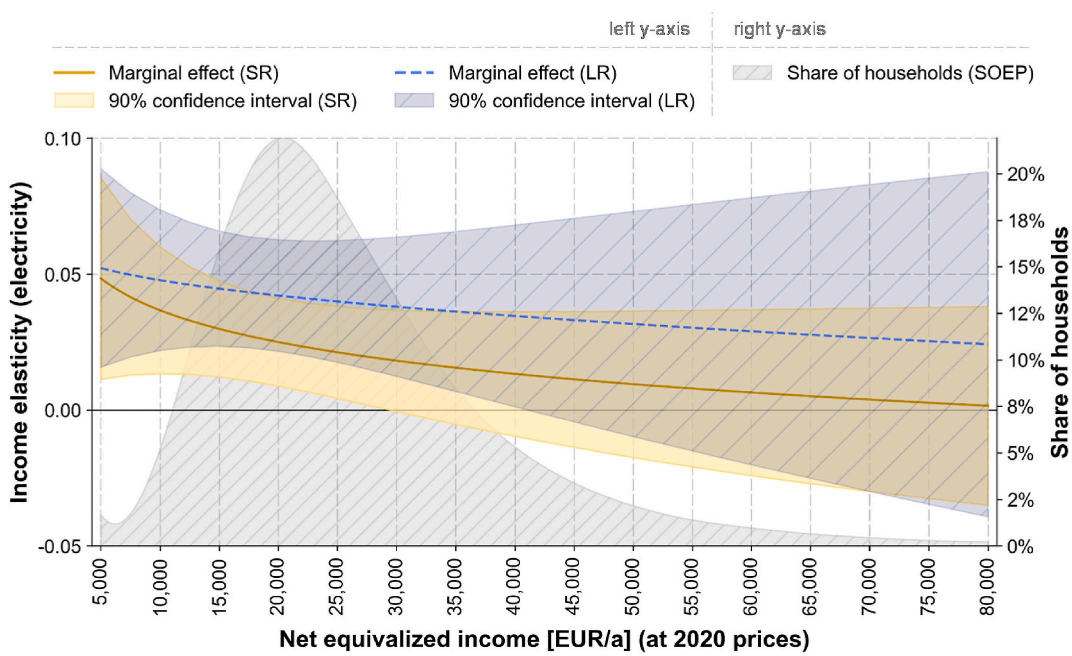

Fig. 5. Income-dependent income elasticities of electricity demand.

reported expenditure is assumed to be independent of the weather situation in the survey years. However, future research using higher-frequency data could explore whether elasticities vary seasonally, particularly for heating demand during winter months, which would inform the design of seasonal pricing policies and targeted assistance programs.

4.4. Price and income elasticities of car fuel demand

The estimation of price and income elasticities of car fuel demand is based on the household and fuel log data of the MOP. Gasoline and diesel are used as a proxy for the general demand for car fuels (which also includes natural gas and electricity). The MOP provides data from 1994 onwards. However, the net household income required for the regression has only been collected since 2004. To avoid distortions due to the influence of the COVID-19 pandemic, the period is again limited up to and including 2019. This results in a total observation period from 2004 to 2019. The fuel log entries are made in the year following the collection of household information. This means that the households surveyed for their household characteristics in 2018 will make their fuel log entries in 2019. Therefore, the information in the fuel log is adjusted for inflation to the previous year and then treated as entries from the previous year. This means that the MOP household sample data is available for the years 2004–2018.

Table 10
Regression results for estimating price and income elasticities of demand for heating energy carriers based on the unit price for natural gas.

	Coefficient	Standard error	[95 % confidence interval]	
$\ln(c^{gas}_{t-1})$	−1.145[a]	(0,115)	−1371	−0,919
$\ln(c^{gas}_{t-1})*\ln(inc)$	0.125[a]	(0,012)	0,102	0,148
$\ln(p^{gas,unit})$	−2.215[a]	(0,363)	−2926	−1504
$\ln(inc)$	−1.104[a]	(0,085)	−1271	−0,938
$\ln(p^{gas,unit})*\ln(inc)$	0.19[a]	(0,037)	0,118	0,263
$\ln\ (inc)^2$	−0.019	(0,009)	−0,036	−0,002
ln(living space)	0.346[a]	(0,022)	0,304	0,389
Household type (Ref.: single-person household)				
Single parent	0.147[a]	(0,017)	0,113	0,181
Couple without children	0.211[a]	(0,021)	0,17	0,253
Couple with children	0.121[a]	(0,024)	0,074	0,168
Other household	0.206[a]	(0,033)	0,142	0,27
At least one university degree available (Ref.: No)				
Yes	−0.018	(0,026)	−0,069	0,034
At least one household member employed (Ref.: No)				
Yes	0.025[b]	(0,011)	0,003	0,046
Year of construction of the residential building (Ref.: before 1949)				
from 1949 and before 1990	−0.066[a]	(0,018)	−0,101	−0,032
from 1990 and before 2001	−0.15[a]	(0,027)	−0,202	−0,098
from 2001	−0.214[a]	(0,034)	−0,281	−0,147
Housing tenure (Ref.: Owner)				
Tenant	0.099[a]	(0,026)	0,048	0,149
Other housing tenure	−0.185	(0,273)	−0,721	0,351
Residential building type (Ref.: single/two-family house)				
Apartment building	−0.082[a]	(0,017)	−0,115	−0,05
Other building type	−0.076[a]	(0,018)	−0,111	−0,042
Average age of adult household members	−0.003[a]	(0,001)	−0,005	−0,002
Dummy variable per federal state	Yes			
Time effects	No			
Budget effects	Yes			
Number of observations	50,165			
Number of households	6138			
R^2 (corrected R)^2	0.2010 (0.2005)			
F-statistics	3573.42***			

Clustered robust standard errors in brackets.
*$p < 0.1$.
[a] $p < 0.01$.
[b] $p < 0.05$.

In contrast to previous studies such as Khanna et al. (2023), households with more than one vehicle are not excluded in our analysis. The number of vehicles correlates with household income. Excluding all households with more than one vehicle would severely restrict the sample, particularly with regard to high-income households. In addition, the number of vehicles correlates with the household size of the household. The calculated equivalence values can be used to control for the formation of the household (see section 3.2). The MOP reports household incomes based on ten income intervals. The household incomes are interpreted as the mean value of the respective interval. After excluding all households without a vehicle and information on household income, the panel sample used for the estimation contains 9760 observations from 5000 households. Table 8 shows the descriptive statistics of the sample used.

The households participating in the MOP have a maximum length of stay in the panel of three years. On average, households remain in the panel for two years. Due to the small number of observations per household, dynamic panel regression is not possible. A static model must therefore be used, which in turn means that no differentiation can be made between short- and long-run elasticities.

Due to the low number of observations per household, a random effects estimation is carried out instead of an estimation with fixed effects. The assumption is made that the unobserved effects of the households are randomly distributed and do not correlate with the regressors. The random effects estimation has the advantage that households with only one valid observation can also be included in the regression (which affects 6 % of the 9760 observations and 12 % of the 5000 households).

Let $c^{car\ fuel}_{i,t}$ be the consumption of car fuels (gasoline and diesel) of a household i at time t, $p^{car\ fuel}_t$ the quantity-weighted average unit price of gasoline and diesel at time t and $inc_{i,t}$ the net equivalized household income i at time t, then the model configuration used is as follows:

$$\ln\left(c^{car\ fuel}_{i,t}\right) = \beta^p \ln\left(p^{car\ fuel}_t\right) + \beta^{inc} \ln\left(inc_{i,t}\right) + \beta^{p\cdot inc} \ln\left(p^{car\ fuel}_t\right)\ln\left(inc_{i,t}\right) + \beta^{inc^2} \ln\left(inc_{i,t}\right)^2 + \boldsymbol{\beta}^T_{\boldsymbol{X}}\boldsymbol{x}_{i,t} + \gamma_i + u_{i,t} \quad (22)$$

5. Results

The estimates for the income-dependent price and income elasticities of energy demand are subsequently presented. A tabular representation of the results for different income groups can be found in Appendix 5.

5.1. Price and income elasticities of electricity demand

The regression coefficient of the interaction term between the electricity unit price and the household income demonstrates that the price elasticity of electricity demand falls as income rises (see Table 9). Given a negative price elasticity, this means that the absolute price elasticity of electricity demand increases with rising income. The regression coefficient of the squared income term is also negative, which means that with an expected positive income elasticity, the income elasticity decreases with increasing income.

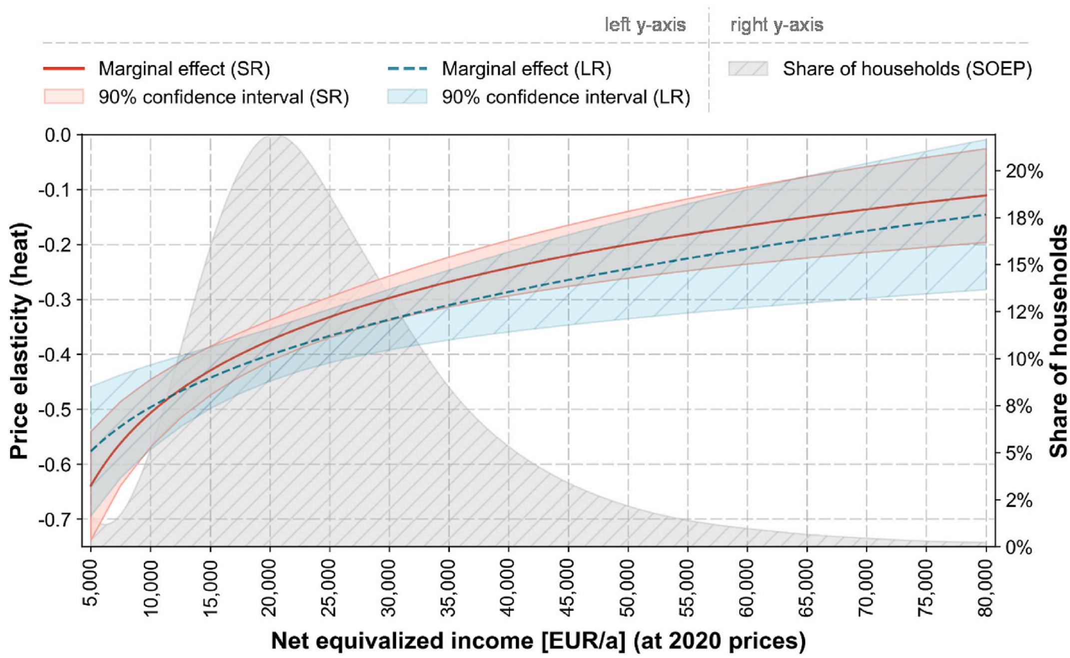

Fig. 6. Income-dependent price elasticities of demand for heating energy carriers.

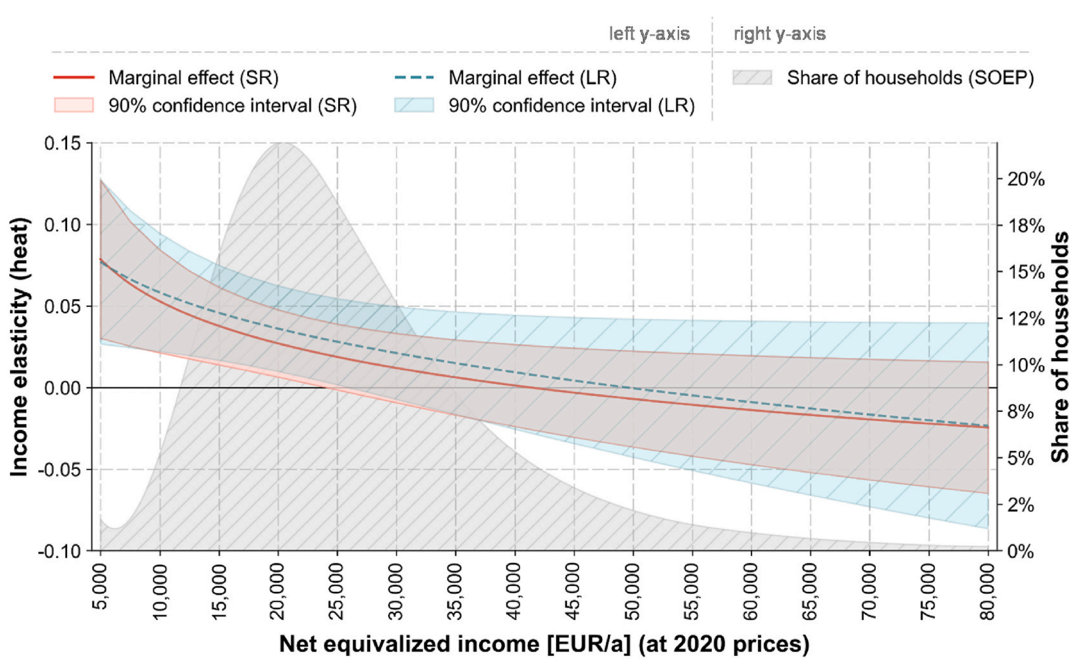

Fig. 7. Income-dependent income elasticities of demand for heating energy carriers.

The interaction term between lagged consumption and income shows that the size of the lag term increases with rising income. Among the other household covariates, the living space, household type, employment status, year of construction of the residential building, type of residential building and electricity-based hot water supply have significant explanatory effects.

Fig. 4 shows the marginal effects according to equations (12) and (15) and 90 % confidence intervals for the short- and long-run income-dependent price elasticities of electricity demand for annual net equivalized household incomes between EUR 5000 and EUR 80,000.

The short-run price elasticity of electricity demand ranges from −0.27 (−0.08 to −0.47) for households with a low net equivalized income (EUR 5000 per year) to −0.44 (−0.25 to −0.62) for households with a high net equivalized income (EUR 80,000 per year). The long-run price elasticity of electricity demand is −0.22 (−0.03 to −0.42) for low-income households, while it rises in absolute terms to −0.64 (−0.31 to −0.97) for high-income households. Accordingly, the effect of a price increase for households with a net equivalized income of up to EUR 15,000 per year is reduced after one year, while it increases for higher-income households. All elasticity values are significant across the entire range of annual net equivalized household incomes from EUR 5000 to EUR 80,000 ($\alpha = 10\%$), as both limits of the confidence interval are below zero. Assigning each household a price elasticity based on its net equivalent income results in an average price elasticity of electricity

Table 11
Regression results for estimating price and income elasticities of propulsion energy for passenger cars.

	Coefficient	Standard error	[95 % confidence interval]	
$\ln(p^{car\ fuel})$	−1.448	(1182)	−3765	0,87
$\ln(inc)$	−2.004[a]	(0,702)	−3381	−0,628
$\ln(p^{car\ fuel})*\ln(inc)$	0.118	(0,121)	−0,118	0,355
$\ln(inc)^2$	0.085[a]	(0,021)	0,045	0,126
Region type (Ref.: Inner city area, large city)				
Outskirts, big city	0.065[b]	(0,028)	0,011	0,12
Inner city area, medium-sized city	0.032	(0,033)	−0,033	0,097
Outskirts, medium-sized city	0.102[a]	(0,03)	0,044	0,159
Small town	0.124[a]	(0,029)	0,067	0,18
Rural area	0.24[a]	(0,029)	0,183	0,297
Household type (Ref.: small household with employed persons)				
Small household without employees	−0.114[a]	(0,043)	−0,199	−0,03
Household with children under 18	−0.048[b]	(0,021)	−0,089	−0,006
Household without children, 3 or more adults	−0.029	(0,027)	−0,082	0,024
At least one university degree available (Ref.: No)				
Yes	0.013	(0,015)	−0,017	0,043
At least one household member employed (Ref.: No)				
Yes	0.073[c]	(0,042)	−0,01	0,156
Average age of adult household members	−0.007[a]	(0,001)	−0,008	−0,005
Average age of the vehicles	−0.009[a]	(0,001)	−0,012	−0,006
Average horsepower of the vehicles	0.003[a]	(0)	0,003	0,004
Dummy variable per federal state	Yes			
Time effects	Yes (squared)			
Budget effects	Yes			
Number of observations	9760			
Number of households	5000			
R^2	0.2230			
Chi-square	1179.71[a]			

Clustered robust standard errors in brackets.
[a] $p < 0.01$.
[b] $p < 0.05$.
[c] $p < 0.1$.

demand of −0.36 (−0.27 to −0.45) in the short run and −0.40 (−0.28 to −0.52) in the long run.

Fig. 5 shows the short- and long-run income-dependent income elasticities of electricity demand according to equations (13) and (16).

The income elasticities of electricity demand are 0.048 (0.011–0.085) for low-income households (EUR 5000 per year) and 0.002 (−0.035 to 0.038) for high-income households (EUR 80,000 per year) in the short run after evaluation at mean values of the unit price and the electricity consumption of the previous year. The short-run income elasticity is no longer significant above a net equivalized income of EUR 29,465 per year, with a final significant value of 0.020 (0.000–0.037). The average value for the entire household sample is 0.023 (0.002–0.044). In the long run, income elasticity ranges between 0.052 (0.016–0.089) and 0.024 (−0.039 to 0.088). It is significant up to a net equivalized income of EUR 41,042 per year with a value of 0.035 (0.000–0.068). The average long-run value for the entire household sample is 0.040 (0.013–0.067).

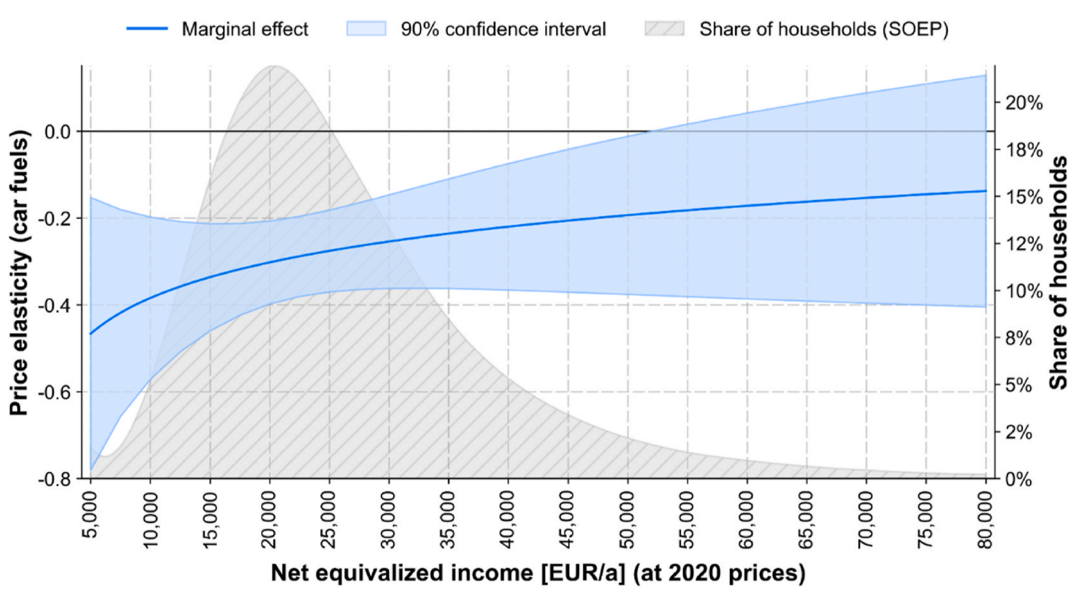

Fig. 8. Income-dependent price elasticities of demand of car fuel demand.

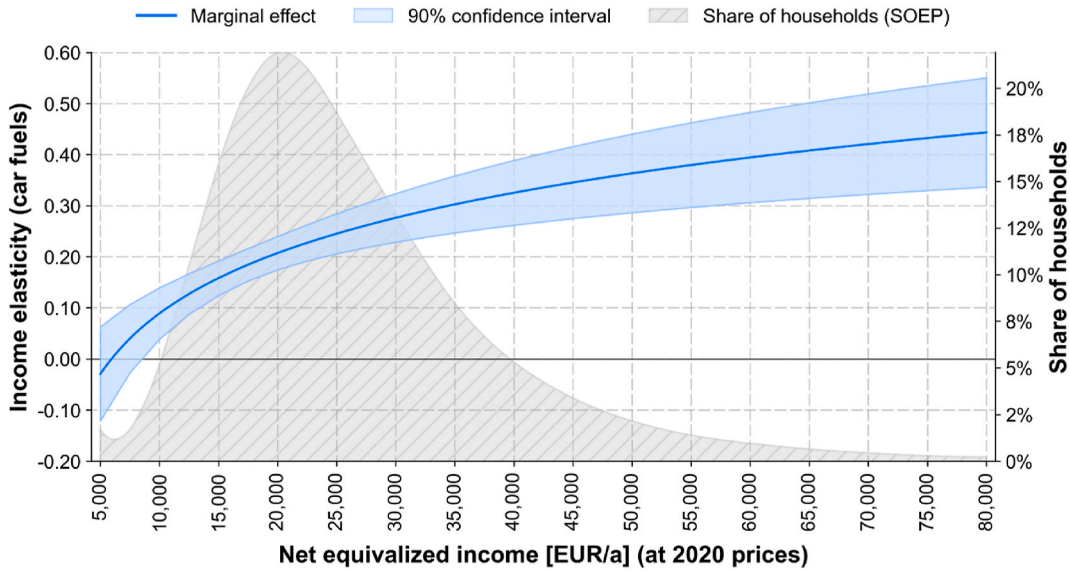

Fig. 9. Income-dependent income elasticities of car fuel demand.

5.2. Price and income elasticities of demand for heating energy carriers

The regression coefficient of the interaction term between the gas unit price and the household income shows that the price elasticity of gas demand increases with rising income (see Table 10). Given a negative price elasticity, this means that the absolute price elasticity of gas demand decreases as income increases. The squared income term is negative, which means that an expected positive income elasticity decreases in absolute terms as income increases. The combined effect of the lagged consumption increases with income. As a result, high-income households react more strongly to price changes in the long than in the short run. Furthermore, the living space, the household type, the employment status, the year of construction of the residential building, the housing tenure, the type of residential building, and the average age of the adult household members have a significant explanatory effect on the gas consumption.

The resulting marginal effects and 90 % confidence intervals for the short- and long-run price elasticities of gas demand for annual net equivalized household incomes between EUR 5000 and EUR 80,000 are shown in Fig. 6.

The short-run income-dependent price elasticity of gas demand lies between −0.64 (−0.54 to −0.74) for households with a low net equivalized income (EUR 5000 per year) and −0.11 (−0.03 to −0.20) for households with a high net equivalized income (EUR 80,000 per year). On average, the short-run price elasticity of gas demand is −0.35 (−0.31 to −0.40). In the long run, the price elasticity ranges between −0.58 (−0.46 to −0.69) and −0.15 (−0.01 to −0.28) and averages −0.38 (−0.31 to −0.44).

The price elasticities are significant in the entire range of annual net equivalized household incomes from EUR 5000 to EUR 80,000 ($\alpha = 10\%$). The effect of price changes on households with an annual net equivalized income of up to EUR 12,000 is slightly lower in the long than in the short run. This fatigue effect suggests that these households have little room for maneuvering when it comes to adjusting their appliance stocks.

The income-dependent income elasticities of gas demand are shown in Fig. 7.

The short-run income elasticity of gas demand for households with a low net equivalized income (EUR 5000 per year) is 0.079 (0.030–0.127). The long-run income elasticities for households with very low and very high incomes hardly differ from the short-run income elasticities, but they are slightly higher for all other income groups. The income elasticities are significant in the short run up to an annual net equivalized household income of EUR 24,104 and in the long run up to an annual net equivalent income of EUR 25,926. At the intersections of the lower confidence intervals with the x-axis, the short-run income elasticity is 0.022 (0.000–0.040), while the long-run elasticity is 0.028 (0.000–0.053).

5.3. Price and income elasticities by drive energy for private transport

Both the interaction term between the car fuel unit price and the net equivalized household income as well as the squared income term are positive (see Table 11). With an expected negative price and positive income elasticity, high-income households have in absolute terms a lower price and a higher income elasticity compared to low-income households. In addition, the region type, the household type, the employment status of the household members, the average age of the adult household members, the average vehicle age, and the average horsepower of the vehicles are significant explanatory variables for car fuel consumption.

The MOP sample does not differentiate incomes above a net monthly household income of EUR 5000. The estimate can therefore only make limited conclusions about households with higher incomes. The average OECD factor for households in the MOP is 1.56. If the monthly income of EUR 5000 is extrapolated to one year and divided by this factor, the result is a net equivalized household income of ~EUR 38,500 per year. Fig. 8 shows the resulting marginal effects and 90 % confidence intervals for the income-dependent price elasticities of car fuel demand.

The price elasticity of car fuel demand is −0.47 (−0.78 to −0.15) for households with a low net equivalized income (EUR 5000 per year) and −0.14 (−0.40 to 0.13) for households with a high net equivalized income (EUR 80,000 per year). The average value of price elasticity for the entire household sample is −0.29 (−0.43 to −0.15). The price elasticity is significant up to a net equivalent income of EUR 52,085 per year, as the upper limit of the confidence interval is above the zero line for higher incomes and is −0.19 (−0.38 to 0.00) at this point. The wide confidence interval at high incomes can be explained by the absence of income differentiation at high net equivalized household incomes.

The income elasticity of car fuel demand is on average 0.226 (0.177–0.276) after evaluation at average car fuel prices. Fig. 9 shows the income-dependent income elasticities.

For low-income households, the income elasticity is significant from a net equivalent income of EUR 8530 per year and is 0.060

Table 12
Literature review of estimated price and income elasticities of private households in Germany (only significant coefficients and no confidence intervals considered).

Authors	Method	Data	Estimates			
			Price elasticity		Income elasticity	
			S	L	S	L
Electricity						
Own estimates	**Dynamic, BCMM**	**SOEP**	**−0.27 to -0.44**	**−0.22 to -0.64**	**0.020 to 0.048**	**0.035 to 0.052**
Frondel et al. (2019)	Dynamic, GMM	GRECS	−0.44	−0.66	0.042	0.063[a]
Held (2017)	Static, center point method	EVS		−0.19 to −0.44		
Madlener et al. (2011)	Dynamic, OLS	IEA energy balances (macro data, country panel)		−0.16		
Nikodinoska and Schröder (2016)	Static, QAIDS	EVS		−0.81		0.507
Pellini (2021)	Dynamic, GMM	IEA energy balances (macro data, country panel)	−0.04	−0.35		
Schulte and Heindl (2017)	Static, QES	EVS		−0.17 to −0.72		0.244 to 0.446
Heating energy carriers						
Own estimates	**Dynamic, BCMM**	**SOEP**	**−0.11 to -0.64**	**−0.15 to -0.58**	**0.022 to 0.079**	**0.028 to 0.077**
Held (2017)	Static, center point method	EVS		−0.11 to −0.94		
Madlener et al. (2011)	Dynamic, OLS	IEA energy balances (macro data, country panel)	−0.15	−0.23		
Rehdanz (2007)	Static, OLS	SOEP		−0.32 to −0.67[b]		0.055 to 0.095
Schmitz and Madlener (2020)	Static, Fixed Effects	SOEP	−0.31 to −0.43		0.026 to 0.092	
Schulte and Heindl (2017)	Static, QES	EVS		−0.21 to −0.92		0.272 to 0.415
Car fuels						
Own estimates	**Static, Random Effects**	**MOP**	**−0.19 to -0.47**		**0.060 to 0.443**	
Dahl (2012)	Static, various	Metastudy		−0.28 to −0.38		1.21 to 1.29
Frondel et al. (2012)	Static, random effects and quantile regression	MOP	−0.55 to −0.90		0.077	
Held (2017)	Static, center point method	EVS		−0.08 to −0.67		
Khanna et al. (2023)	Static, Pooled OLS	MOP	−0.38 to −0.86		0.031	
Nikodinoska and Schröder (2016)	Static, QAIDS	EVS		−0.084		0.832
Schulte and Heindl (2017)	Static, QES	EVS		−0.30 to −0.86		0.400 to 0.677

SOEP: Socio-Economic Panel; EVS: Income and Consumption Survey; MOP: German Mobility Panel; BCMM: Bias-Corrected Method of Moments; GMM: Generalized Method of Moments; QES: Quadratic Expenditure System; QAIDS: Quadratic Almost Ideal Demand System.
[a] Own recalculation based on the reported regression results.
[b] Partly own recalculation, as the stated price elasticities of demand for heating oil are not consistent with those of the price elasticity of expenditure on heating oil.

(0.000–0.120) at this point. For high-income households (EUR 80,000 per year), it rises to 0.443 (0.336–0.550). While low-income households tend to spend less additional income on mobility, the opposite is true for high-income households. The latter can be explained, for example, by the purchase of cars with greater horsepower or additional vehicles.

5.4. Validation

To validate the estimated price and income elasticities, we compare our results with estimates from other studies. Table 12 summarizes the results of the meta-analysis on price and income elasticities of private households in Germany.

The reported elasticities vary greatly, but some patterns can be identified. For example, the short-run price and income elasticities for the demand for electricity and heating energy carriers are on average lower than the corresponding long-run elasticities. The price elasticities are generally negative and are in the inelastic range (absolute values are less than one). The income elasticities are consistently greater than zero.

The elasticities estimated in this study fit into the range of comparative values. The large differences between the various studies can be attributed to methodological differences (both with regard to the model and estimation procedure used and the explanatory variables selected) and to differences in the underlying data.

6. Conclusion

We have investigated residential short- and long-run price and income elasticities of electricity, gas, and car fuel demand as a function of household income. We exploit longitudinal data from two large private household samples and apply method of moments and OLS estimators to fixed and random effects models.

Our results not only align with the existing literature but advance the field in several key dimensions. While previous studies have demonstrated the existence of heterogeneity in energy demand responses, our work provides the first comprehensive income-dependent elasticity functions across multiple energy carriers for German households. Unlike studies that report only directional effects of income on elasticities, our approach enables policymakers to determine precise elasticity values for any income level through continuous functions. This granular analysis reveals critical policy-relevant insights not captured in previous work, such as the finding that gas price elasticities become insignificant for high-income households above certain thresholds, while car fuel price responsiveness varies dramatically across the income distribution. Furthermore, our integration of bias-corrected dynamic panel methods with commodity-specific equivalence scales provides more robust elasticity estimates than static approaches or those relying solely on income-based scaling. These methodological advances, combined with our multi-decade panel data spanning three energy carriers, offer policymakers a tool for designing income-differentiated energy policies that account for both short- and long-run behavioral responses.

We find that price elasticities of demand vary across energy carriers, income levels, and time horizons. For electricity, short-run elasticities range from −0.27 for low-income households to −0.44 for high-income households, while long-run elasticities span from −0.22 to −0.64. Gas price elasticities exhibit an inverse relationship with income, ranging between −0.64 for low-income and −0.11 for high-income households in the short run and from −0.58 to −0.15 in the long run. For car fuels, short- and long-run price elasticities could not be differentiated. Car fuel demand shows price elasticities from −0.47 for low-income to −0.14 for high-income households, becoming insignificant above €52,085 annual net equivalized household income. Average price elasticities across all households are −0.36 (short-run) and −0.40 (long-run) for electricity, −0.35 (short-run) and −0.38 (long-run) for gas, and −0.29 for car fuels.

Income elasticities of demand vary across energy carriers and income levels. For electricity, short-run income elasticities range from 0.048 for low-income households to 0.002 for high-income households, becoming insignificant at annual net equivalized incomes above EUR 29,465. Long-run elasticities are slightly higher, ranging from 0.052 to 0.024. For gas, short-run income elasticities are significant up to EUR 24,104 annual net equivalized household income, with low-income households at 0.079. Long-run elasticities for gas are marginally higher across most income groups. Car fuel elasticities increase with income from 0.060 for low-income households to 0.443 for high-income households.

Following a price increase, low-income households tend to reduce their gas and car fuel consumption more than high-income households. In contrast, high-income households tend to make stronger adjustments to their electricity consumption (excluding the consumption of electricity for heating and transportation) in response to a price change. The consumption of electricity and heating energy carriers increases the most for low-income households as a result of an increase in income, while the consumption of car fuels increases the most for high-income households.

We observe that low-income households show signs of fatigue when faced with a price increase, resulting in decreased absolute consumption changes in the long run. Studies on energy poverty have shown that low-income households may reduce energy consumption to the extent that health is negatively affected. This should be taken into account when designing price-based incentives.

CRediT authorship contribution statement

Jan Priesmann: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Aaron Praktiknjo:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices

Appendix 1

Table 13
Private households final energy consumption in 2022

Category	Value	Unit	Year	Source
Private households				
Total consumption	994.5	TWh		
- thereof electricity	134.1	TWh	2022	AGEB (2024)
- thereof natural gas	248.5	TWh	2022	
-thereof other energy carriers	290.7	TWh	2022	
-thereof car fuels (gasoline and diesel)	321.2	TWh	2021	Destatis (2023)
All Sectors				
Total consumption	2365.9	TWh	2022	AGEB (2024)
-thereof electricity	477.5	TWh	2022	
-thereof natural gas	555.8	TWh	2022	
-thereof other energy carriers	1.332,6	TWh	2022	
-thereof car fuels (gasoline and diesel)	532.9	TWh	2022	
Share of private households				
Total consumption	44.4	%		
-thereof electricity	28.1	%		
-thereof natural gas	44.7	%		
-thereof other energy carriers	21.8	%		
-thereof car fuels (gasoline and diesel)	60.3	%		

Table 14
Private households GHG emissions in 2022

Category	Value	Unit	Year	Source
Private households				
Total GHG emissions	243,964.4	kt CO_2-eq	2022	
- thereof electricity	57,544.4	kt CO_2-eq	2022	(AGEB, 2024; UBA, 2024b)
- thereof district heat	14,112.4	kt CO_2-eq	2022	(AGEB, 2024; UBA, 2023b)
- thereof other energy carriers	85,502.4	kt CO_2-eq	2022	UBA (2023a)
- thereof car fuels	86,805.2	kt CO_2-eq	2022	(Destatis, 2023; UBA, 2023a)
All Sectors				
Total GHG emissions	754.344,8	kt CO_2-eq	2022	UBA (2023a)
Share of private households				
Total GHG emissions	32.3	%		

7.2 Appendix 2

Table 15
Identifiers in the SOEP sample of variables used in this study.

Variablenkategorie	hgen	hl	hpathl	hbrutto	hwealth	pgen	ppathl	pequiv
Haushalts-ID	hid	hid	hid	hid	hid	hid	hid	Hid
Personen-ID						pid	pid	pid
Erhebungsjahr	syear	syear	syear	syear	syear	syear	syear	Syear
Erhebungsmonat	hghmonth							
Haushaltszusammen-setzung (Anzahl der Bewohner, Alter der Bewohner, Art des Haushalts)	hgtyp1hh	hlc0043		hgr			gebjahr	
Geschlecht der Haushaltsmitglieder							sex	
Höchster Ausbildungsabschluss der Haushaltsmitglieder						pgpbbil02		
Erwerbsstatus der Haushaltsmitglieder						pglfs		
Wohnung (Baujahr, Gebäudetyp, Wohnfläche, Eigentum)	hgcnstyrmin, hgcnstyrmax, hgsize, hgowner			wum1				
Bundesland	hgnuts1							
Elektrizität (Ausgaben, eigene Erzeugung)	hgelectr	hlf0084, hlf0035						
Wärmeenhergieträger, gesamt (Ausgaben)	hgheat	hlf0090_h						
Gas (Ausgaben)		hlf0549, hlf0555, hli0042_h						
Heizöl (Ausgaben)		hlf0568, hli0036_h						
Fernwärme (Ausgaben)		hlf0543, hli0047_h						
Kraftstoffe (Ausgaben)		hli0105, hli0091, hli0098						
Heizungsanlage		hlf0540, hlf0541, hlf0545, hlf0546, hlf0551, hlf0552, hlf0557, hlf0558, hlf0564, hlf0565, hlf0570, hlf0571, hlf0576, hlf0577, hlf0582, hlf0583, hlf0587, hlf0588, hlf0589, hlf0590, hli0032, hli0033, hli0038, hli0039, hli0044, hli0045, hli0049, hli0050, hli0056, hli0057, hli0061, hli0062						
Haushaltsnetto-einkommen	hghinc							i11102
Haushaltsvermögen					w011ha			
Klimaanlage		hlf0034						
Instandhaltungs-ausgaben		hlf0089_v2						
Hochrechnungsfaktor			hhrf					

Table 16
Identifiers in the MOP sample of variables used in this study.

Variablenkategorie	HH	TANK	P	POT	KIND
Haushalt-ID	ID	ID	ID	ID	ID
Personen-ID			PERSNR	PERSNR	PERSNR
Fahrzeug-ID		PKWNR			
Erhebungsjahr	JAHR	JAHR	JAHR	JAHR	JAHR
Geburtsjahr der Haushaltsmitglieder			GEBJAHR	GEBJAHR	GEBJAHR
Geschlecht der Haushaltsmitglieder			SEX	SEX	SEX
Höchster Ausbildungsabschluss der Haushaltsmitglieder			SCHULAB	SCHULAB	
Erwerbsstatus der Haushaltsmitglieder			BERUF	BERUF	
Haushaltsnettoeinkommen	EINKO				
Lage der Wohnung	LAGE				
Haushaltstyp	HHTYP				
Anzahl der Bewohner	HHGRO, P0_10				
Anzahl an Fahrzeugen	PKWHH				
Kraftstofftyp		BENZIN, ANTRIEB			
Baujahr		BAUJAHR			
Hubraum		HUBRAUM			
Leistung		PS			
Aufzeichnungsdauer		TAGE			
Datum des Tankvorgangs		DAT1, …DAT26			
Getankte Treibstoffmenge		LITER1, …, LITER26			
Im Berichtszeitraum verbrauchte Treibstoffmenge		GESLITER			
Ausgaben für Tankvorgang		PREIS1, …, PREIS26			
Hochrechnungsfaktor	GEWHHWO				

7.3 Appendix 3

The equivalence values for net household income and expenditure on electricity, heating energy carriers, and car fuels are validated using the following household types.

- H0: Single-person household
- H1: Single parents with one child
- H2: Couple without children
- H3: Couple with two children

Fig. 10 shows the validation results. Both scaling using the OECD scale and using the newly calculated equivalence values leads to an equalization of the economies of scale in households. Scaling based on the OECD scale leads to an underestimation of the savings effects for expenditure on energy carriers, which is particularly evident in the case of heating energy carriers. The higher equivalized values for household type H2 (couple without children) according to the new scale for expenditure on electricity and gas can be explained by the fact that this household type also has the highest net equivalized income. Therefore, the savings effects for this household type are more than compensated for by deliberate additional expenditure, such as larger heated living spaces.

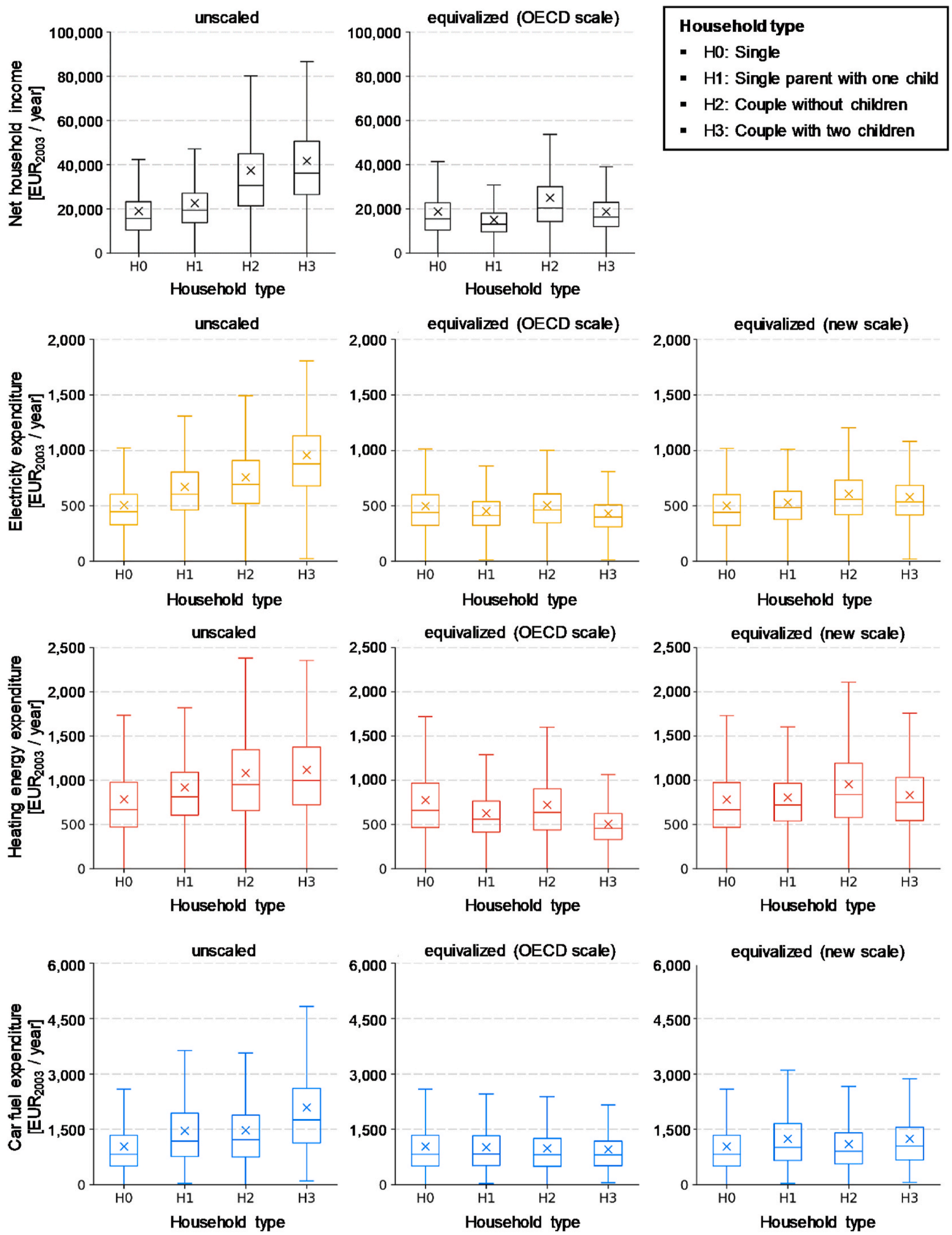

Fig. 10. Validation of the equivalence factors for net household income and expenditure on electricity, heating energy carriers and car fuels.

7.4 Appendix 4

Table 17

Nominal average prices for electricity, natural gas, district heating, wood pellets, coal, heating oil, petrol and diesel for private households. Based on data from BDEW (2024a, 2024b), Destatis (2024b), the European Commission (2024) and AGEB (2023).

Year	Electricity	Natural gas	District heating	Wood pellets	Coal	Heating oil	Gasoline	Diesel
	[EUR-ct/kWh]					[EUR-ct/l]		
1991	12.38	3.99	–	–	–	26.40	73.50	54.80

(*continued on next page*)

Table 17 (*continued*)

Year	Electricity	Natural gas	District heating	Wood pellets	Coal	Heating oil	Gasoline	Diesel
	[EUR-ct/kWh]					[EUR-ct/l]		
1992	12.87	4.02	–	–	–	24.20	76.70	54.20
1993	13.18	3.98	–	–	–	24.80	78.10	55.50
1994	13.47	3.95	–	–	–	23.10	86.60	58.50
1995	13.64	3.83	–	–	–	21.90	86.70	57.80
1996	12.84	3.76	–	–	–	25.90	89.80	62.40
1997	12.92	3.91	–	–	–	26.60	85.20	63.70
1998	13.07	3.92	–	–	–	22.10	81.20	58.70
1999	13.58	3.83	–	–	–	26.50	86.70	63.90
2000	12.92	4.45	–	–	–	40.80	101.80	80.40
2001	13.44	5.40	–	–	–	38.40	102.40	82.20
2002	14.04	5.09	–	–	–	35.10	104.80	83.80
2003	14.75	5.35	–	–	–	36.20	109.50	88.80
2004	15.35	5.41	–	–	–	40.30	114.00	94.20
2005	15.98	5.97	–	–	–	53.20	122.30	106.70
2006	16.61	7.02	–	–	–	58.90	128.90	111.80
2007	17.75	7.23	–	–	–	58.20	134.40	117.00
2008	18.98	7.87	–	–	–	76.50	139.90	133.50
2009	20.16	7.75	–	–	–	53.00	127.80	108.50
2010	20.81	7.08	–	–	–	65.00	141.50	122.40
2011	22.33	7.42	–	–	–	81.00	155.40	141.90
2012	22.96	7.82	–	–	–	88.10	164.60	148.90
2013	25.67	7.92	–	–	–	82.25	159.20	142.80
2014	26.16	7.92	–	–	–	76.40	152.80	135.00
2015	25.96	7.79	11.22	3.07	5.68	58.80	139.40	117.10
2016	26.07	7.63	10.68	3.03	5.65	48.85	129.60	107.21
2017	26.47	7.40	10.35	3.15	5.66	56.61	136.55	115.58
2018	26.82	7.30	10.53	3.18	5.66	68.89	145.64	128.87
2019	27.73	7.47	11.00	3.24	5.65	67.29	143.19	126.72
2020	28.59	7.56	10.78	3.12	5.64	49.88	129.26	112.43
2021	28.96	7.85	10.89	3.14	5.70	70.73	157.95	139.92
2022	34.54	11.63	13.56	4.94	7.39	132.35	192.59	196.04
2023	38.91	14.63	14.93	5.27	11.15	103.38	184.87	173.73

7.5 Appendix 5

Table 18
Summary of the estimated price elasticities of energy demand.

Net equivalent income (at 2020 prices)	Electricity				Heating energy carriers				Car fuels	
	SR		LR		SR		LR		–	
5000	−0.27	UB: 0.08	−0.22	UB: 0.03	−0.64	UB: 0.54	−0.58	UB: 0.46	−0.47	UB: 0.15
		LB: 0.47		LB: 0.42		LB: 0.74		LB: 0.69		LB: 0.78
10,000	−0.31	UB: 0.20	−0.29	UB: 0.17	−0.51	UB: 0.45	−0.50	UB: 0.42	−0.38	UB: 0.20
		LB: 0.43		LB: 0.41		LB: 0.57		LB: 0.57		LB: 0.57
15,000	−0.34	UB: 0.26	−0.34	UB: 0.25	−0.43	UB: 0.39	−0.44	UB: 0.39	−0.34	UB: 0.21
		LB: 0.41		LB: 0.42		LB: 0.47		LB: 0.50		LB: 0.46
20,000	−0.35	UB: 0.29	−0.37	UB: 0.30	−0.37	UB: 0.34	−0.40	UB: 0.35	−0.30	UB: 0.21
		LB: 0.42		LB: 0.45		LB: 0.41		LB: 0.45		LB: 0.40
25,000	−0.37	UB: 0.30	−0.41	UB: 0.32	−0.33	UB: 0.30	−0.37	UB: 0.32	−0.28	UB: 0.18
		LB: 0.43		LB: 0.49		LB: 0.37		LB: 0.42		LB: 0.37
30,000	−0.38	UB: 0.30	−0.43	UB: 0.33	−0.30	UB: 0.26	−0.34	UB: 0.28	−0.25	UB: 0.15
		LB: 0.46		LB: 0.54		LB: 0.34		LB: 0.39		LB: 0.36
35,000	−0.39	UB: 0.30	−0.46	UB: 0.33	−0.27	UB: 0.22	−0.31	UB: 0.25	−0.24	UB: 0.11
		LB: 0.48		LB: 0.59		LB: 0.31		LB: 0.37		LB: 0.36
40,000	−0.40	UB: 0.29	−0.48	UB: 0.33	−0.24	UB: 0.19	−0.29	UB: 0.21	−0.22	UB: 0.07
		LB: 0.50		LB: 0.64		LB: 0.29		LB: 0.36		LB: 0.37
45,000	−0.40	UB: 0.28	−0.51	UB: 0.33	−0.22	UB: 0.16	−0.26	UB: 0.18	−0.21	UB: 0.04
		LB: 0.52		LB: 0.69		LB: 0.28		LB: 0.35		LB: 0.37
50,000	−0.41	UB: 0.28	−0.53	UB: 0.33	−0.20	UB: 0.14	−0.24	UB: 0.15	−0.19	UB: 0.01
		LB: 0.54		LB: 0.73		LB: 0.26		LB: 0.34		LB: 0.38
55,000	−0.41	UB: 0.27	−0.55	UB: 0.32	−0.18	UB: 0.12	−0.23	UB: 0.13	−0.18	UB: 0.02
		LB: 0.56		LB: 0.77		LB: 0.25		LB: 0.33		LB: 0.38
60,000	−0.42	UB: 0.27	−0.57	UB: 0.32	−0.17	UB: 0.10	−0.21	UB: 0.10	−0.17	UB: 0.04
		LB: 0.57		LB: 0.82		LB: 0.24		LB: 0.32		LB: 0.39
65,000	−0.42	UB: 0.26	−0.59	UB: 0.32	−0.15	UB: 0.08	−0.19	UB: 0.08	−0.16	UB: 0.07
		LB: 0.59		LB: 0.86		LB: 0.22		LB: 0.31		LB: 0.39
70,000	−0.43	UB: 0.26	−0.60	UB: 0.31	−0.14	UB: 0.06	−0.18	UB: 0.05	−0.15	UB: 0.09
		LB: 0.60		LB: 0.89		LB: 0.21		LB: 0.30		LB: 0.40
75,000	−0.43	UB: 0.25	−0.62	UB: 0.31	−0.12	UB: 0.04	−0.16	UB: 0.03	−0.15	UB: 0.11

(*continued on next page*)

Table 18 (*continued*)

Net equivalent income (at 2020 prices)	Electricity				Heating energy carriers				Car fuels	
	SR		LR		SR		LR		–	
80,000	−0.44	LB: 0.61 UB: 0.25 LB: 0.62	−0.64	LB: 0.93 UB: 0.31 LB: 0.97	−0.11	LB: 0.21 UB: 0.03 LB: 0.20	−0.15	LB: 0.29 UB: 0.01 LB: 0.28	−0.14	LB: 0.40 UB: 0.13 LB: 0.40

SR: Short-run; LR: Long-run.
UB: Upper Bound (upper limit of the 90 % confidence interval); LB: Lower Bound (lower limit of the 90 % confidence interval).

Table 19
Summary of the estimated income elasticities of energy demand.

Net equivalent income (at 2020 prices)	Electricity				Heatin energy carriers				Car fuels	
	SR		LR		SR		LR		–	
5000	0.048	UB: 0.011 LB: 0.085	0.052	UB: 0.016 LB: 0.089	0.079	UB: 0.030 LB: 0.127	0.077	UB: 0.027 LB: 0.127	−0.029	UB: 0.121 LB: 0.063
10,000	0.037	UB: 0.013 LB: 0.060	0.048	UB: 0.022 LB: 0.074	0.053	UB: 0.021 LB: 0.084	0.058	UB: 0.022 LB: 0.094	0.089	UB: 0.038 LB: 0.139
15,000	0.030	UB: 0.012 LB: 0.047	0.045	UB: 0.023 LB: 0.066	0.038	UB: 0.014 LB: 0.061	0.046	UB: 0.017 LB: 0.075	0.158	UB: 0.124 LB: 0.192
20,000	0.025	UB: 0.009 LB: 0.041	0.042	UB: 0.022 LB: 0.063	0.027	UB: 0.006 LB: 0.048	0.036	UB: 0.010 LB: 0.062	0.207	UB: 0.174 LB: 0.240
25,000	0.021	UB: 0.004 LB: 0.038	0.040	UB: 0.018 LB: 0.062	0.019	UB: 0.001 LB: 0.039	0.028	UB: 0.002 LB: 0.054	0.245	UB: 0.206 LB: 0.284
30,000	0.018	UB: 0.001 LB: 0.037	0.038	UB: 0.012 LB: 0.064	0.012	UB: 0.009 LB: 0.033	0.021	UB: 0.007 LB: 0.049	0.276	UB: 0.229 LB: 0.324
35,000	0.016	UB: 0.005 LB: 0.036	0.036	UB: 0.007 LB: 0.066	0.006	UB: 0.017 LB: 0.029	0.015	UB: 0.017 LB: 0.046	0.302	UB: 0.247 LB: 0.358
40,000	0.013	UB: 0.010 LB: 0.036	0.035	UB: 0.001 LB: 0.068	0.001	UB: 0.024 LB: 0.026	0.009	UB: 0.026 LB: 0.044	0.325	UB: 0.262 LB: 0.389
45,000	0.011	UB: 0.014 LB: 0.036	0.033	UB: 0.004 LB: 0.070	−0.003	UB: 0.030 LB: 0.024	0.004	UB: 0.034 LB: 0.043	0.345	UB: 0.275 LB: 0.416
50,000	0.009	UB: 0.017 LB: 0.036	0.032	UB: 0.010 LB: 0.073	−0.007	UB: 0.036 LB: 0.022	0.000	UB: 0.043 LB: 0.042	0.363	UB: 0.286 LB: 0.440
55,000	0.008	UB: 0.021 LB: 0.037	0.030	UB: 0.015 LB: 0.076	−0.011	UB: 0.042 LB: 0.021	−0.005	UB: 0.051 LB: 0.041	0.379	UB: 0.296 LB: 0.462
60,000	0.006	UB: 0.024 LB: 0.037	0.029	UB: 0.020 LB: 0.078	−0.014	UB: 0.047 LB: 0.019	−0.009	UB: 0.059 LB: 0.041	0.394	UB: 0.306 LB: 0.483
65,000	0.005	UB: 0.027 LB: 0.037	0.028	UB: 0.025 LB: 0.080	−0.017	UB: 0.052 LB: 0.018	−0.013	UB: 0.066 LB: 0.040	0.408	UB: 0.314 LB: 0.501
70,000	0.004	UB: 0.030 LB: 0.037	0.026	UB: 0.030 LB: 0.083	−0.020	UB: 0.056 LB: 0.017	−0.017	UB: 0.073 LB: 0.040	0.421	UB: 0.322 LB: 0.519
75,000	0.003	UB: 0.032 LB: 0.038	0.025	UB: 0.035 LB: 0.085	−0.022	UB: 0.061 LB: 0.016	−0.020	UB: 0.080 LB: 0.040	0.432	UB: 0.330 LB: 0.535
80,000	0.002	UB: 0.035 LB: 0.038	0.024	UB: 0.039 LB: 0.088	−0.025	UB: 0.065 LB: 0.016	−0.023	UB: 0.087 LB: 0.040	0.443	UB: 0.336 LB: 0.550

SR: Short-run; LR: Long-run.
UB: Upper Bound (upper limit of the 90 % confidence interval); LB: Lower Bound (lower limit of the 90 % confidence interval).

Data availability

Data will be made available on request.

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